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Quantitative assessment of food safety interventions for *Campylobacter* spp. and *Salmonella* spp. along the chicken meat supply chain in Burkina Faso and Ethiopia

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ABSTRACT

Rural and small-scale chicken farming is a major source of income in most African countries, and chicken meat is an important source of nutrients. However, chicken meat can be contaminated with *Campylobacter* spp. and *Salmonella* spp., pathogens with a high reported burden of foodborne illnesses. Therefore, it is essential to control these pathogens in chicken meat. Quantitative microbial risk assessments (QMRA) can aid the development of effective food safety control measures and are currently lacking in chicken meat supply chains in the African context. In this study, we developed stochastic QMRA models for *Salmonella* spp. and *Campylobacter* spp. in the chicken meat supply chain in Burkina Faso and Ethiopia employing the modular process risk model in @Risk software. The study scope covered chicken farming, transport, slaughtering, consumer handling, and consumption. Effectiveness of candidate interventions was assessed against baseline models' outputs, which showed that the mean annual *Campylobacter* spp. risk estimates were 6482 cases of illness per 100,000 persons and 164 disability adjusted life years (DALYs) per 100,000 persons in Burkina Faso, and 12,145 cases and 272 DALYs per 100,000 persons in Ethiopia. For *Salmonella* spp., mean annual estimates were 2713 cases and 1212 DALYs per 100,000 persons in Burkina Faso, and 4745 cases and 432 DALYs per 100,000 persons in Ethiopia. Combining interventions (improved hand washing plus designated kitchen utensils plus improved cooking) resulted in 75 % risk reduction in Burkina Faso at restaurants and 93 to 94 % in Ethiopia at homes for both *Salmonella* spp. and *Campylobacter* spp. For Burkina Faso, adding good hygienic slaughter practices at the market to these combined interventions led to over 91 % microbial risk reduction. Interventions that involved multiple food safety actions in a particular step of the supply chain or combining different interventions from different steps of the supply chain resulted in more risk reduction than individual action interventions. Overall, this study demonstrates how diverse and scanty food supply chain information can be applied in QMRA to provide estimates that can be used to stimulate risk-based food safety action in African countries.

1. Introduction

In developing countries such as Burkina Faso and Ethiopia, chickens are important for the economic survival of especially the rural population (Guèye, 2000; FAO, 2019). However, chickens and chicken meat are introduced to foodborne pathogens along the supply chain by exposure factors during farming (Newell and Fearnley, 2003), transport (Whyte et al., 2001), slaughter (Kagambèga et al., 2018), meat processing (Rasschaert et al., 2008) and consumer handling practices (Katiyo et al., 2019). In Africa, a significant burden of foodborne diseases has been estimated (Havelaar et al., 2015) and among the top ranked pathogens are *Campylobacter* spp. and *Salmonella* spp. (Havelaar et al., 2015; Hoffmann et al., 2017), which are commonly associated with chicken meat.

Recently in Burkina Faso and Ethiopia, it has been reported that foodborne diseases due to *Campylobacter* spp. caused the largest number of cases, while foodborne diseases due to *Salmonella* spp. caused the largest number of deaths and disability adjusted life years (DALYs)

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(Havelaar et al., 2022). Although outputs of quantitative microbial risk assessments (QMRA) are helpful to direct food safety control measures, in African countries such as Burkina Faso and Ethiopia, these assessments are scanty (Benamar et al., 2021; Manyori et al., 2017; Pouillot et al., 2012) and, if available, do not cover the entire food supply chain due to the complexity of these chains, limited data, and expertise. Therefore, in this study we aim to (i) develop a QMRA model to estimate the risk of campylobacteriosis and salmonellosis due to consumption of chicken meat in Burkina Faso and Ethiopia, identify data gaps and direct data collection for future QMRA studies; and (ii) identify and determine the effectiveness of selected risk-based interventions to control and reduce foodborne illnesses associated with *Salmonella* spp. and *Campylobacter* spp. along the chicken meat supply chain.

2. Materials and methods

2.1. Scope of the QMRA

This QMRA study covered the chicken meat supply chain from “farm to fork.” Based on the modular process risk model (MPRM) approach (Nauta et al., 2005a) and as shown in Fig. 1, five main modules were chosen: (i) at farm, (ii) during transport of live chickens before market, (iii) at live and slaughter markets, (iv) during after-market transport of carcasses (only in Burkina Faso) and (v) at consumer level (homes/street vendors/restaurants). The population at risk was the entire population of each of the two countries (Burkina Faso and Ethiopia) after determining the risk exposure for cooks that prepare and also consume chicken meat and those individuals who only consume meat but do not prepare. Six routes of pathogen transmission in Burkina Faso and seven routes in Ethiopia were included in the model at serving and treated in

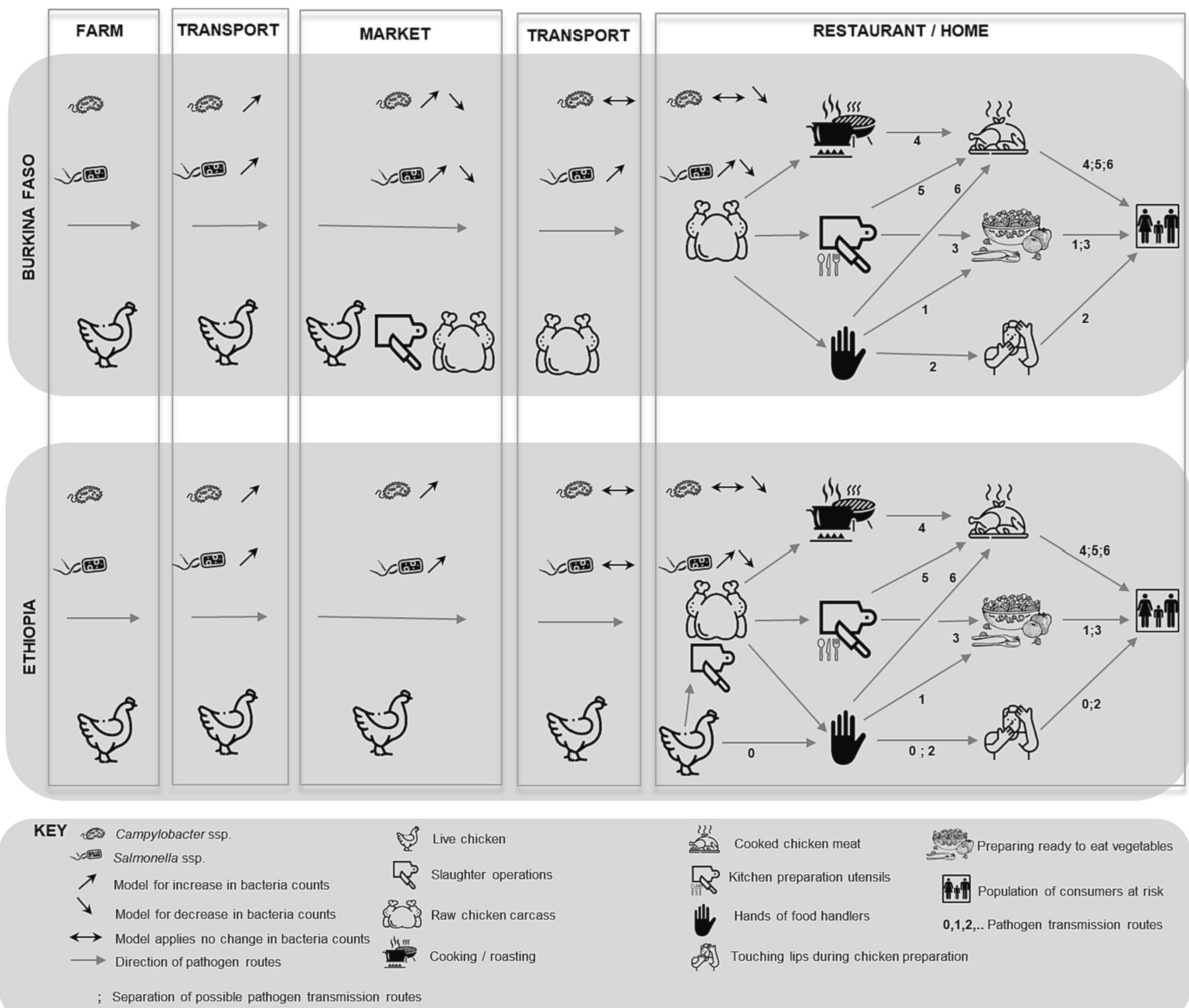

Fig. 1. Conceptual model framework for the chicken meat supply chain in Burkina Faso and Ethiopia and the associated risk exposure routes through which *Campylobacter* spp. and *Salmonella* spp. can be transmitted and ingested by humans. The numbers (0, 1, 2, 3, 4, 5, 6) show the different pathogens transmission pathways (routes) and their model sequence in ascending order. 0) Live chickens — hands — touching lips — ingestion. 1) Carcass — hands — ready-to-eat fresh salad — ingestion. 2) Carcass — hands — touching lips — ingestion. 3) Carcass — cutting boards and other utensils — ready-to-eat fresh salad — ingestion. 4) Carcass — undercooked chicken meat — ingestion. 5) Carcass — cutting boards and other utensils — cooked chicken meat — ingestion. 6) Carcass — hands — cooked chicken meat — ingestion. Photo credit: Icons from free pick at flaticon.com.

parallel to provide insight into the risk of each route separately, since it is possible that not all routes would occur at once to one person at a serving event. Finally, the overall risk per random serving was determined by combining all the routes.

2.2. Model overview

Fig. 1 provides an overview of the modelled chicken meat supply chain in Burkina Faso and Ethiopia. This overview was derived from the descriptions provided by Dione et al. (2021) in Burkina Faso and Amenu et al. (2021) in Ethiopia. We used this overview to define the baseline chicken meat supply chain conditions, which represent the most common conditions of the supply chain (Dogan et al., 2019; Nauta et al., 2005b). Other supply chains such as import were excluded because over 90 % of chicken meat in both countries is from domestically raised chickens (Dione et al., 2021; Amenu et al., 2021) and to keep a balance between complexity and simplicity (Zwietering, 2009). Complex QMRA are less transparent, more uncertain because of more data gaps and are less researchable due to more time needed and costs.

Four baseline models, one for each combination of country and pathogen, were developed to estimate the risk of campylobacteriosis and salmonellosis and the healthy life years lost (in DALYs) due to consumption of chicken meat and ready-to-eat (RTE) vegetables in a meal in Burkina Faso and Ethiopia and the cook's behavior of touching lips with contaminated hands. Four models were developed because of inherent differences between the pathogens and structural differences of the chicken meat supply chain between the countries. The baseline model for *Salmonella* spp. in Burkina Faso can be found in Table 1 and for *Campylobacter* spp. in Appendix A, and for *Campylobacter* spp. in Ethiopia in Appendix B and for *Salmonella* spp. in Ethiopia in Appendix C. *Campylobacter* spp. baseline models assumed that there is no growth on chicken meat along the different steps of the supply chain (Duffy and Dykes, 2006) and no nonthermal inactivation, while for *Salmonella* spp. growth models were incorporated, following the approach of Pouillot et al. (2012) in Senegal. Lag time was not considered as *Salmonella* spp. are considered to be part of the resident microflora of live chickens, with enough time to adapt to the chicken carcass environment.

Apart from hazard identification, which was predetermined, our models followed the next standard steps of conducting QMRA that involve exposure assessment (Section 2.3), hazard characterization (Section 2.4) and risk characterization (Section 2.5) (FAO and WHO, 2021). Data used to populate the models came from country specific published and grey literature and from work packages of the project on "Urban Food Markets in Africa – incentivizing food safety (Pull-Push Project)" (Knight-Jones, 2021). In case no data were found for Burkina Faso and Ethiopia, data from other countries were used with priority to African and other developing countries, and expert opinion. In cases where surrogate data were used, focus on data from various countries was favored to single country data, if available, and thereafter systematic reviews and meta-analyses were conducted to obtain model inputs (Appendix D). Data were incorporated into the models with distributions to describe either uncertainty or variability or both (Collineau et al., 2020b), however, for some model inputs, fixed (constant) estimates were applied depending on the nature of available data. Moreover, sensitivity towards uncertainty for specified model inputs were conducted by scenario analyses like in the study of Benamar et al. (2021). In their study, Benamar et al. (2021) were not able to quantify total uncertainty due to numerous sources of uncertainty, and the varied character of the uncertainties. The QMRA models were coded into an Excel spreadsheet and simulated with @Risk software (version 8.2, Palisade Corporation, New York, USA) settings of Latin Hypercube sampling, Mersenne Twister generator and 1,000,000 iterations. The number of iterations was determined when the risk estimates were stable after several rounds of simulations with a random seed setting and thereafter a fixed seed (1) was used in all further simulations. Each iteration of the model tracks one chicken at the farm, that goes through the next supply chain steps; transport, market, slaughtering, preparation and cooking and finally served as cooked chicken with RTE.

2.3. Exposure assessment

In the exposure assessment, the chicken meat supply chains' conditions were assessed to determine changes in prevalence, concentration and numbers of *Salmonella* spp. and *Campylobacter* spp. on live chickens and carcasses at each step of the supply chain. Model simulations were conducted to show how prevalence and concentration changed from farm to the time of consumption at restaurants in Burkina Faso and at home in Ethiopia (see Appendix E, Fig. E.1 and E.2). The final microbial counts (dose) per serving and probability of exposure were fed into in the hazard and risk characterization parts of the QMRA. For some iterations, doses of less than one colony forming unit (CFU) were included although it can be argued that these doses do not occur in nature. Nevertheless, the beta-Poisson dose response model used in this study (Section 2.4) can integrate this effect (ILSI Europe, 2010) and an expected dose of for example 0.1 CFU/serving means that the dose is 1 CFU in 10 % of the servings. Similar to the study of Dogan et al. (2019), prevalence in this study refers to ratio of contaminated units to the total number, while concentration refers to the contamination load per positive unit in log colony forming units (Log_{10}CFU). Chicken meat consumers in Burkina Faso (Dione et al., 2021) and Ethiopia (Amenu et al., 2021) prefer freshly slaughtered chicken meat and for this reason the QMRA models in this study did not include an upper limit of pathogens based on the carcass storage temperature time combinations (2 to 7 days) where spoilage can occur and limit consumption (FAO/WHO 2002). However, during growth of *Salmonella* spp., the upper limit of $N(t)$ was set at 1.0×10^8 CFU/cm^2 as the maximum achievable viable cell count (Pouillot et al., 2012).

2.3.1. Farm and live chicken transport module

The farm (module 1) and live chicken transport (module 2) were built to estimate the external contamination and prevalence of *Salmonella* spp. and *Campylobacter* spp. on live chickens (Table 1 and Appendix A, B, C). For colonized chickens, external concentration was calculated as a function of the number of cells (in CFU) of these pathogens in chicken feces at the chicken house and estimated amount of feces (in g) on the exterior of live chickens at the time of selling (Collineau et al., 2020b). Prevalence data were scarce for chickens from small scale village farms in Burkina Faso and Ethiopia, so studies from neighboring countries were used (Table 1, Appendix A, B), except for *Salmonella* spp. in Ethiopia (Appendix C). During transport of live chickens from farm to market, vendors buy and collect about 100 chickens from different farms in a village to obtain the required number for resell or slaughter. Transport of live chickens can lead to an increased level of contamination due to stress and cross-contamination (Whyte et al., 2001) (see Appendix E, Fig. E.1). To obtain the number of pathogens on positive chicken exterior after transport, the external pathogen counts on chickens at farm was multiplied by a transport load increase factor (Collineau et al., 2020b). Prevalence was computed as a function of probability of cross-contamination between positive and negative chickens (Collineau et al., 2020b).

2.3.2. Market and slaughter module

After arrival at the marketplace, live chickens are held in cages until slaughter in Burkina Faso or resold live to consumers in Ethiopia. For this, we used the same modelling approach as at the farm to model the change in microbial concentration. To cater for prevalence changes, the transport module approach was used (Section 2.3.1 and Table 1). For both countries, slaughter is performed manually using knives. In Burkina Faso, several chickens are slaughtered at once at market, while in Ethiopia one or two live chickens are slaughtered at home. The slaughter process has four successive processing steps: scalding, defeathering, evisceration and washing (Dione et al., 2021). The change in prevalence

Table 1
Summary of variables and parameters used in the Quantitative Microbial Risk Assessment (QMRA) model for *Salmonella* spp. in Burkina Faso.

Variable symbol	Variable description	Distribution/formula	Units	Data source/reference/assumption
	Farm			
	Prevalence			
P_{farms}	Prevalence of *Salmonella* spp. for chicken reared in small village farming system	Risk Uniform (0, 0.46, RiskTruncate (0,1)	Prevalence	Andoh et al., 2016; Raufu et al., 2009; Dione et al., 2009; Orji et al., 2005: Studies from countries near to Burkina Faso
Pos_{farms}	Positive live chicken at farm level	Risk Binomial (1, P_{farms})	No units	1 = live chicken positive with *Salmonella* spp., 0 = negative
	Concentration			
C_{feces}	Log concentration of *Salmonella* spp. in feces	Risk Pert (0, 3.579, 4.294)	$\log_{10}$CFU/g	Collineau et al., 2020a: Estimates from Canada, but by expert opinion, concentration in feces can also apply to chicken in Burkina Faso.
A_{feces}	Amount of feces on live chicken exterior at pre-harvest	Risk Triangular (1, 10, 50)	g	Collineau et al., 2020b
$N_{exterior}$	Number of bacteria on exterior of live chicken at pre-harvest	$(10\hat{}C_{feces}) * A_{feces}$	CFU/live chicken	Calculated
	Transport of live chickens			
	Prevalence			
Co_{trans}	Contact chance between live chickens during transport	Risk Binomial (1,1)	Probability	We assume that the live chickens transported on bicycles and vehicles have 100 % chance of making a contact with each other
$Pb_{crossch}$	Probability for cross-contamination between live chickens to occur	$1\text{-}(1\text{-}P_{farms})\hat{}(Co_{trans})$	Probability	Calculated
$P_{Lchtrans}$	Prevalence of *Salmonella* spp. on live chickens after transport	$P_{farms} + (1\text{-}P_{farms}) * Pb_{crossch}$	Prevalence	Calculated
	Concentration			
FC_{trans}	Increase factor of contamination load during transport	Constant 10ˆ0.15	No units	Collineau et al., 2020b
N_{trans}	Number of bacteria on positive live chicken exterior after transport	$IF(Pos_{farms} = 0, 0, N_{exterior} * FC_{trans})$	CFU/live chicken	Calculated
	Market			
	Display of live chickens			
	Within cage prevalence			
Co_{cage}	Contact chance between live chickens in market cages	Risk Binomial (1, 1)	Probability	We assume that the live chickens held in a cage at market have 100 % chance of making a contact with each other
$Pb_{crosscage}$	Probability for cross-contamination between live chickens	$1\text{-}(1\text{-}P_{Lchtrans})\hat{}(Co_{cage})$	Probability	Calculated
P_{mcage}	Prevalence of *Salmonella* ssp. for live chickens in market cages	$P_{Lbtrans} + (1\text{-}P_{Lbtrans})*Pb_{crosscage}$	Prevalence	Calculated
	Concentration			
$C_{fecesmkt}$	Log concentration of *Salmonella* ssp. in feces	Risk Pert (0, 3.579, 4.294)	$\log_{10}$CFU/g	Assumed to be the same as at farm
$A_{fecesmkt}$	Amount of additional feces on live chicken exterior at market	Risk Triangular (1, 10, 50)	g	Assumed to be the same as at farm
N_{extmkt}	Number of additional bacteria on live chicken exterior at market	$(10\hat{}C_{fecesmkt}) * A_{fecesmkt}$	CFU/live chicken	Calculated
N_{before}	External contamination of live chicken at market before slaughter	$N_{trans} + N_{extmkt}$	CFU/live chicken	Calculated
	Market slaughtering (processing)			Live chicken turns to carcass
	Scalding			
OR_{scald}	Change in prevalence due to scalding (odds ratio)	Risk Lognorm2 (−1.71, 0.63)	Odds ratio	Dogan et al., 2019; Dogan et al., 2022: Systematic review and meta-analysis data for *Campylobacter* spp.
P_{scald}	Resulting prevalence after scalding	$P_{mcage} * OR_{scald} / (1\text{-}P_{mcage} + (P_{mcage} * OR_{scald}))$	Prevalence	Calculated
LC_{scald}	Change in log concentration due to scalding	Risk Triangular Alt (2.5 %, −1.52, 50 %, −1.022, 97.5 %, −0.524)	$\log_{10}$Change	Appendix D: Systematic review and meta-analysis, data for Enterobacteriaceae before and after soft scalding
C_{scald}	Resulting log concentration after scalding	$IF(N_{before} = 0, 0, \log_{10}N_{before} + LC_{scald})$	$\log_{10}$CFU/ carcass	Calculated
	Defeathering			
OR_{Def}	Change in prevalence due to defeathering (odds ratio)	Risk Lognorm2 (0.20, 0.34)	Odds ratio	Dogan et al., 2019; Dogan et al., 2022: Systematic review and meta-analysis data for *Campylobacter* spp.
P_{Def}	Resulting prevalence after defeathering	$P_{scald} * OR_{Def} / (1\text{-}P_{scald} + (P_{scald} * OR_{Def}))$	Prevalence	Calculated
LC_{Def}	Change in log concentration due to defeaturing	Risk Uniform (0.01, 0.4)	$\log_{10}$Change	Pacholewicz et al., 2016: Data for *Campylobacter* spp. during manual defeaturing
C_{Def}	Resulting log concentration after defeathering	$C_{scald} + LC_{Def}$	$\log_{10}$CFU/ carcass	Calculated
	Evisceration			
OR_{Evi}	Change in prevalence due to evisceration (odds ratio)	Risk Lognorm2 (0.12, 0.13)	Odds ratio	Dogan et al., 2019; Dogan et al., 2022: Systematic review and meta-analysis data for *Campylobacter* spp.
P_{Evi}	Resulting Prevalence after evisceration	$P_{Def} * OR_{Evi} / (1\text{-}P_{Def} + (P_{Def} * OR_{Evi}))$	Prevalence	Calculated

(*continued on next page*)

Table 1 (*continued*)

Variable symbol	Variable description	Distribution/formula	Units	Data source/reference/assumption
LC_{Evi}	Change in log concentration due to evisceration	Risk Triangular Alt (2.5 %, 0.049, 50 %, 0.256, 97.5 %, 0.464)	log_{10}Change	Appendix D: Systematic review and meta-analysis, data for Enterobacteriaceae before and after evisceration
C_{Evi}	Resulting log concentration after evisceration	$C_{Def} + LC_{Evi}$	log_{10}CFU/carcass	Calculated
	Washing			
OR_{Wash}	Change in prevalence due to washing (odds ratio)	Risk Lognorm2 (−0.25, 0.36)	Odds ratio	Dogan et al., 2019; Dogan et al., 2022: Systematic review and meta-analysis data for *Campylobacter* spp.
P_{wash}	Resulting Prevalence after washing	P_{Evi} * OR_{Wash} / (1-P_{Evi} + (P_{Evi} * OR_{Wash}))	Prevalence	
Wash	Positive carcass after washing at local market	Risk Binomial (1, P_{wash})	No units	Positive = 1 and Negative = 0
LC_{Wash}	Change in log concentration due to washing	Risk Normal (−0.582, 1.068, Risk Truncate (−3.83, 1.041))	log_{10}Change	Field data from Burkina Faso from a related work package
$C_{washmkt}$	Resulting log concentration after washing	CEvi +LC_{Wash}	log_{10}CFU/carcass	Calculated
	Transport of chicken carcasses			
	Growth during transport carcass at street restaurant			
	Secondary growth model			
T_{trans}	Transport temperature	Risk Pert (22.5, 28.6, 35.6)	degree C	Climate-Data.Org, 2020
t_{transt}	Transport time	Risk Uniform (0,2)	hours	Dione et al., 2021
	Cardinal model parameters			
T_{min}	Minimum temperature for growth	Constant 5.7	°C	Pouillot et al., 2012
T_{max}	Maximum temperature for growth	Constant 49.3	°C	Pouillot et al., 2012
T_{opt}	Optimal temperature for growth	Constant 40	°C	Pouillot et al., 2012
μ_{opt}	Optimal growth rate on chicken skin	Constant 0.732	log_{10}CFU/h	Oscar, 2002
K_{num}	Cardinal model numerator	(T_{trans} -T_{max}) * (T_{trans} -T_{min}) ^{2}	°C	Pouillot et al., 2012
K_{deno}	Cardinal model denominator	(T_{opt} -T_{min}) * [(T_{opt} -T_{min}) * (T_{trans} -T_{opt}) - (T_{opt} -T_{max}) * (T_{opt} + T_{min} -2T_{trans})]	°C	Pouillot et al., 2012
μT_{trans}	Growth rate on chicken skin at the transport temperature	IF(OR ($T_{trans} \leq T_{min}$, $T_{trans} \geq T_{max}$), 0, (μ_{opt} * (K_{num}/K_{deno})))	log_{10}CFU/h	Pouillot et al., 2012
	Primary growth model			
C_{max}	Maximum achievable viable log cell count	Constant 8	$log_{10}CFU/cm^2$	Pouillot et al., 2012
BSA	Entire chicken body surface area	Risk Normal (1232, 165)	cm^2/carcass	Pouillot et al., 2012; Gill and Badoni, 2005
C_{transt}	Log Number of cells on carcass after transport time to home/restaurant	IF(10^$C_{washmkt} \leq$ 0, 0, log_{10}(10^$C_{washmkt}$*10^(μT_{trans}*t_{transt})))	log_{10}CFU/carcass	Calculated
N_{tra}	Number of cells on carcass after transport to home/restaurant	IF(10^C_{transt} > (10^C_{max}*BSA), (10^C_{max}*BSA),10^C_{transt})	CFU/carcass	Calculated
	Consumer level: restaurant/home			
	Growth during holding carcass at home			
	Secondary growth model			
T_{hold}	Carcass Holding temperature	Risk Pert (22.5, 28.6, 35.6)	°C	Dione et al., 2021
t_{hold}	holding time	Risk Pert (2.5, 3.4, 5.9)	h	Dione et al., 2021
K_{num2}	Cardinal model numerator	(T_{hold} -T_{max}) * (T_{hold} -T_{min})^2	°C	Calculated
K_{deno2}	Cardinal model denominator	(T_{opt} -T_{min}) * [(T_{opt} -T_{min}) * (T_{hold} -T_{opt}) - (T_{opt} -T_{max}) * (T_{opt} + T_{min} -2T_{hold})]	°C	Calculated
μT_{hold}	Growth rate on chicken skin at the holding temperature	IF(OR($T_{hold} \leq T_{min}$, $T_{hold} \geq T_{max}$), 0, (μ_{opt} * (K_{num2} / K_{deno2})))	log_{10}CFU/h	Calculated
C_{ht}	Log Number of cells on carcass after holding time	IF(N_{tra} ≤0, 0, (Log_{10}(N_{tra}*10^(μT_{hold}*t_{hold}))))	log_{10}CFU/carcass	Calculated
N_{hold}	Number of cells on carcass after holding	IF(10^C_{ht} > (10^C_{max}*BSA), (10^C_{max}*BSA), 10^C_{ht})	CFU/carcass	Calculated
	Cells on carcass that can be involved in cross contamination			In the study by FAO and WHO (2009), a drip fluid model was used, and it was assumed that only a fraction of loosely attached pathogenic cells on the chicken carcass are involved in cross-contamination. In this study, we also use this fraction but not the entire drip fluid model and assumed that the cells in this fraction are all part of the contact zone.
F_{loose}	Fraction of loosely attached cells	Risk Uniform (0.01, 0.1)	Proportion	
N_{loose}	Number of loosely attached cells on a carcass	N_{hold}*F_{loose}	CFU/carcass	Calculated
	Portioning and preparation (cross contamination)			
	Route 1: Carcass — hands — RTE[◇] — ingestion			
Tf_{CH2}	Transfer from chicken to hands?	IF(Wash = 0, 0, 1)	No units	Transfer is only possible for a contaminated carcass
$Prop_{CH}$	Proportion of cells transferred from chicken to hands	Risk LogNorm (0.0444, 0.112, Risk Shift (0.00114))	Proportion	Luber et al., 2006
N_{CH2}	Number of cells on hands	IF(Tf_{CH2} = 0, 0, (IF(N_{loose} = 0, 0, N_{loose}*$Prop_{CH}$)))	CFU/both hands	
N_{left1}	Number left on chicken carcass	IF(N_{CH2} > N_{loose}, 0, (N_{loose} - N_{CH2}))	CFU/carcass	
Pb_{HW}	Probability that hands are washed	RiskBeta (36 + 1, 39–36 + 1)	Probability	Dione et al., 2021

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Table 1 (*continued*)

Variable symbol	Variable description	Distribution/formula	Units	Data source/reference/assumption
Pb_{notHW}	Probability that hands are not washed	1- Pb_{HW}	Calculated	
HW	Hands not washed?	Risk Binomial (1, Pb_{notHW})	No units	1 = hands not washed, 0 = hands washed
Pb_{CKRTE}	Probability of preparing chicken with other ready to eat (RTE) foods	Risk Beta (24 + 1, 100–24 + 1)	Probability	Dione et al., 2021
INC_{RTE}	Including RTE in meal	Risk Binomial (1, Pb_{CKRTE})	No units	1 = RTE included, 0 = RTE not included
$Prop_{HF}$	Proportion of cells transferred from hands to RTE	Risk Pert (0.07, 0.182, 0.38)	%	Verhoeff-Bakkenes et al., 2008
N_{RTEH2}	Number of cells on RTE via hands that can be consumed	IF(INC_{RTE} = 0, 0, IF(HW = 0, 0, N_{CH2}* $Prop_{HF}$/100))	CFU/whole portion of RTE	Calculated
$WT_{chicken}$	Weight of edible whole chicken carcass	Risk Pert (800, 920, 1000)	g/Carcass	Kondombo, 2005
$CK_{eatprop}$	Proportion of chicken consumed per person	Risk Pert (1/8, 1/4, 1/1)	Proportion	Unpublished field data from Burkina Faso from a related project work package
$SER_{chicken}$	Serving size of chicken per person	$WT_{chicken}$ *$CH_{eatprop}$	g/person	Calculated
NP_{served}	Average number of persons served per chicken	$WT_{chicken}$ /$SER_{chiciken}$	Persons/carcass	Calculated
D_{RTE}	Number of bacterial cells in ready to eat vegetables per person served (Dose)	N_{RTEH2}/ NP_{served}	CFU	Calculated
Pbex1	Probability of exposure through contaminated RTE	P_{wash} * Pb_{CKRTE} * Pb_{notHW}	Probability	Calculated
	Route 2: Carcass — hands — lips — ingestion			
N_{HL3}	Number of cells left on hands after handling RTE at home	N_{CH2}-N_{RTEH2}	CFU/both hands	Calculated
$Prop_{HMH}$	Proportion of cells transferred from hands tips to mouth	Pert (0.339, 0.363, 0.41)	Proportion	Rusin et al., 2002
N_{lips}	Number of cells transferred to lips and thereafter swallowed	IF(HW = 0, 0, (N_{HL3}*$Prop_{HMH}$))	CFU /lips	
Pb_{touch}	Probability of touching the mouth	Risk Beta (372 + 1, 652 + 1)	Probability	Kwok et al., 2015
M_{touch}	Touching the mouth	Risk Binomial (1, Pb_{touch})	No units	1 = Touching the mouth, 0 = not
D_{Tmouth}	Total number of cells ingested by the cook touching the mouth (Dose)	IF (M_{tough} = 0, 0, N_{lips})	CFU	Calculated
Pbex2	Probability of exposure through contaminated fingers touching the mouth	P_{wash} * Pb_{touch}* Pb_{notHW}	Probability	Calculated
	Route 3. Carcass — cutting boards and other utensils — RTE — ingestion			
Pb_{ntwute}	Probability that utensils used are not washed properly	Risk Beta (10 + 1, 100–10 + 1)	Probability	Dione et al., 2021; washing surface before chicken preparation at restaurants
Tf_{CB}	Transfer from chicken to board	IF(N_{left1} = 0, 0, 1)	No units	Transfer is only possible for a contaminated carcass
$Prop_{CB}$	Proportion of cells transferred from chicken carcass to the board	Risk Pert (0, 0.0395, 0.217)	Proportion	Bai et al., 2021: Risk Pert distribution derived from experimental data conducted with different cutting board materials, plastic, wood, bamboo washed with cold water and hot water
N_{CB}	Number of cells on board (set of kitchen utensils)	IF(Tf_{CB} = 0, 0, N_{left1}*$Prop_{CB}$)	CFU/set of utensils	Calculated
N_{left2}	Number left on the chicken carcass	N_{left1} - N_{CB}	CFU/carcass	Calculated
Pb_{CBBRTE}	Probability that the cutting board and utensils used for cutting raw chicken are also used for RTE foods	Risk Beta (19 + 1, 40–19 + 1)	Probability	Dione et al., 2021, restaurants that used the same knife in all kitchen slaughter operations
B_{RTE}	Boards used for RTE foods?	Risk Binomial (1, Pb_{CBBRTE})		
$Prop_{BRTE}$	Proportion of cells transferred from board to RTE foods	Risk Pert (0.0532, Average (0.0532, 0.128, 0.163), 0.163)	Proportion	Bai et al., 2021
N_{CBRTE}	Number of cells on RTE from raw chicken via kitchen utensils	IF(B_{RTE} = 0, 0,IF(N_{CB} < 0, 0, N_{CB}*$Prop_{BRTE}$))	CFU/whole portion of RTE	Calculated
D_{UteRTE}	Number of cells on RTE from chicken via kitchen utensils per person served (Dose)	N_{CBRTE}/ NP_{served}	CFU/serving portion of RTE	Calculated
Pbex3	Probability of exposure to utensils contaminating RTE	Pb_{ntwute} * P_{wash}*Pb_{CBBRTE}	Probability	Calculated
	Route 4. Undercooking — ingestion			
Pb_{inadC}	Probability of inadequate cooking	Risk Pert (0.05, 0.1, 0.15)	Probability	FAO and WHO, 2002
AC	Adequately cooked?	Risk Binomial (1, (1-Pb_{inadC}))	No units	1 = adequately cooked, 0 = not
$Prop_{prot}$	Proportion of cells in areas that permit a chance of survival	Risk Pert (0.01, 0.016, 0.02) * 0.1	Proportion	We divide the proportions used in the FAO and WHO, 2002; by factor of 10 to account for the roasting/cooking methods described in Burkina Faso (Dione et al., 2021)
N_{atch}	Number of cells on carcass strongly attached and not involved in cross contamination	N_{hold}-N_{loose}	CFU/carcass	Calculated
N_{rem}	Number of cells remaining on carcass after cross contamination events	N_{atch} + N_{left2}	CFU/carcass	Calculated
C_{Prot}	Log number of cells with chance of survival	IF(N_{rem} = 0, 0, log_{10}(N_{rem}* $Prop_{Prot}$))	log_{10}CFU	FAO and WHO, 2002
t_{Prot}	Exposure time at exposure temp for cells in' protected area'	Risk Pert (0.50, 1.00, 1.50)	minutes	FAO and WHO, 2002
Tmp_{Prot}	Exposure temp during cooking in 'protected areas'	Risk Pert (60, 64, 65)	degree C	FAO and WHO, 2002
D_{Prot}	D-value (at this temp)	10^(−0.139*Tmp_{Prot} + 8.58)	minutes	FAO and WHO, 2002

(*continued on next page*)

Table 1 (*continued*)

Variable symbol	Variable description	Distribution/formula	Units	Data source/reference/assumption
$CProt_{LR}$	Log reduction in 'protected area'	IF(AC = 1,"death", t_{Prot}/D_{Prot})	log_{10}Change	Calculated
C_{surv}	Total log number of cells surviving cooking	IF($Prot_{LR}$ = "death", 0, C_{Prot} - $CProt_{LR}$)	log_{10}CFU	Calculated
N_{surv}	Number of cells surviving cooking on whole cooked chicken	IF(C_{surv} = 0, 0, 10^C_{surv})	CFU/carcass	Calculated
D_{Uncook}	Number of cells surviving cooking served per person (**Dose**)	N_{surv} / NP_{served}	CFU/serving	Calculated
Pbex4	Probability of exposure to undercooking	Pb_{inadC} * P_{wash}	Probability	Calculated
	Route 5. Carcass — Cutting boards and other utensils — cooked chicken — ingestion			
N_{CBleft}	Number of cells left on the board after preparation other RTE foods	N_{CB} – N_{CBRTE}	CFU/ set of utensils	Calculated
Pb_{RC}	Probability that same board (or utensils) are used for both raw & cooked chicken	Risk Beta (16 + 1, 100–16 + 1)	Probability	Dione et al., 2021; for restaurants that did not wash surface at start, end and between dishes, assuming the chicken is not hot to kill the pathogens
BU_{use}	Board and utensils use	Risk Binomial (1, Pb_{RC})	No units	1 = same utensils used, 0 = not
Tf_{BCK}	Transmission rate of cells from board and utensils to cooked chicken	Risk Pert (0.105, 0.194, 0.424)	Proportion	Smadi et al., 2013
N_{wckute}	Number of cells on whole cooked after transfer from contaminated utensils	IF(BU_{use} = 0, 0, IF(N_{CBleft} < 0, 0, N_{CBleft} * Tf_{BCK}))	CFU/whole cooked	Calculated
$D_{UtecookCK}$	Number on cooked chicken from raw chicken via board (or utensils) (**Dose**)	N_{wckute} / NP_{served}	CFU	Calculated
Pbex5	Probability of exposure to cross contamination from utensils to cooked chicken	Pb_{RC} * P_{wash}* Pb_{ntwute}	Probability	Calculated
	Route 6. Carcass— hands — cooked chicken — ingestion			
N_{CHleft}	Number of cells left on the hands after preparation other RTE foods	N_{HL3} - D_{Tmouth}	CFU/both hands	Calculated
Tf_{HCK}	Transmission rate of cells from hands to cooked chicken	Risk Pert (0.001, 0.089, 0.529)	Proportion	Smadi and Sargeant, 2013
N_{wckhd}	Number of cells on whole cooked after transfer from contaminated hands	IF(HW = 0, 0, IF(N_{CHleft} < 0, 0, N_{CHleft} * Tf_{HCK}))	CFU/carcass	Calculated
$D_{hdcookCK}$	Number on cooked chicken from raw chicken via hands served per person (**Dose**)	N_{wckhd} / NP_{served}	CFU/serving	Calculated
Pbex6	Probability of exposure to cross contamination from unwashed hands to cooked chicken	Pb_{notHW} * P_{wash}	Probability	Calculated
	Hazard characterization			
	Beta Poisson model parameter			
α	Alpha parameter	Constant 0.1324	No units	FAO and WHO, 2002
β	Beta parameter	Constant 51.45	No units	FAO and WHO, 2002
B	Beta distribution for beta Poisson model parameters	Risk Beta (0.1324, 51.45)	No units	FAO and WHO, 2002
	Probability of infection given a dose of bacteria (*P_{infecD}*) = Probability of illness (P_{ill}) given a contaminated serving via a specific route:			
$Pill_{RTE}$	Route 1: Carcass — hands — RTE◊ — ingestion	1-(1-B)^^{DRTE}	Probability	Calculated
$Pill_{tmouth}$	Route 2: Carcass — hands — lips — ingestion	1-(1-B)^^{DTmouth}	Probability	Calculated
$Pill_{UteRTE}$	Route 3. Carcass — Cutting boards and other utensils — RTE — ingestion	1-(1-B)^^{DUteRTE}	Probability	Calculated
$Pill_{Uncook}$	Route 4. Undercooking — ingestion	1-(1-B)^^{DUncook}	Probability	Calculated
$Pill_{UtecookCK}$	Route 5. Carcass — cutting boards and other utensils — cooked chicken — ingestion	1-(1-B)^^{DUtecookCK}	Probability	Calculated
$Pill_{hdcookCK}$	Route 6. Carcass— hands — cooked chicken — ingestion	1-(1-B)^^{DhdcookCK}	Probability	Calculated
	Risk characterization			
	Risk per serving			
ri1	Route 1: Carcass — hands — RTE◊ — ingestion	$Pill_{RTE}$ * Pbex1	Risk per serving	Calculated
ri2	Route 2: Carcass — hands — lips — ingestion	$Pill_{tmouth}$ * Pbex2	Risk per serving	Calculated
ri3	Route 3. Carcass — Cutting boards and other utensils — RTE — ingestion	$Pill_{UteRTE}$ * Pbex3	Risk per serving	Calculated
ri4	Route 4. Undercooking — ingestion	$Pill_{Uncook}$ * Pbex4	Risk per serving	Calculated
ri5	Route 5. Carcass — cutting boards and other utensils — cooked chicken — ingestion	$Pill_{UtecookCK}$ * Pbex5	Risk per serving	Calculated
ri6	Route 6. Carcass— hands — cooked chicken — ingestion	$Pill_{hdcookCK}$ * Pbex6	Risk per serving	Calculated
	Overall probability of illness per serving: at individual level			

(*continued on next page*)

Table 1 (*continued*)

Variable symbol	Variable description	Distribution/formula	Units	Data source/reference/assumption
ri_{cook}	Overall risk per random serving for a cook (person involved in chicken preparation and eat)	1-((1-ri1) * (1-ri2) * (1-ri3) * (1-ri4) * (1-ri5) * (1-pi6))	Risk per serving	Calculated: Persons who are involved in chicken preparation can touch their lips with contaminated fingers
ri_{eat}	Overall risk per random serving for a person who only eat	1-((1-ri1) * (1-ri3) * (1-ri4) * (1-ri5) * (1-ri6))	Risk per serving	Calculated
	Number of cases at population level			
Rp	Risk population in Burkina Faso	Constant 20,500,000	Persons	UNFPA, 2021
$Prop_{pcook}$	Proportion of the population that is involved in food preparation	Constant 3/25	Proportion	Ratio of average number restaurant employees to average number of customers served per day as from unpublished field data from Burkina Faso from a related work package
Bp_{prep}	Population of people who are involved in food preparation (cooks)	$Rp*Prop_{pcook}$	Persons	Calculated
Bp_{eat}	Population of people who eat but not involved in food preparation	$Rp-Bp_{prep}$	Persons	Calculated
P_{low}	Proportion of the population classified as low-income earners	Constant 0.614	Proportion	PEW Research Center, 2021
P_{mid}	Proportion of the population classified as middle-income earners	Constant 0.318	Proportion	PEW Research Center, 2021
P_{high}	Proportion of the population classified as high-income earners	Constant 0.068	Proportion	PEW Research Center, 2021
FoC_{low}	Frequency of chicken meat consumption for low-income people	Risk Pert (0, 4, 8)	Year $^{-1}$	Dione et al., 2021 and This study⊕
FoC_{mid}	Frequency of chicken meat consumption for middle income people	Risk Pert (0, 2, 4) per month * 12	Year $^{-1}$	Dione et al., 2021 and This study⊕
FoC_{high}	Frequency of chicken meat consumption for high income people	RiskPert (0, 2, 4) per week * 52.14	Year $^{-1}$	Dione et al., 2021 and This study⊕
$AvFoC_{ET}$	Weighted average frequency of chicken meat consumption	$(FoC_{low} * P_{low} + FoC_{mid} * P_{mid} + FoC_{high} * P_{high})/ (P_{low} + P_{mid} + P_{high})$	Year $^{-1}$	Calculated
$Nprep_{year}$	Number of servings consumed per year by chicken cooks in Burkina Faso	$AvFoCET * Bp_{prep}$	Preparation. persons/year	Calculated
$NSer_{year}$	Number of servings consumed per year by consumers not involved in cooking in Burkina Faso	$AvFoCET * Bp_{eat}$	Servings/year	Calculated (a serving = one person)
TNc_{cook}	Number of cases involved in preparation and eating	$Nprepyear * ri_{cook}$	Cases/year	Calculated
TNc_{eat}	Number of cases who only eat but do not prepare (meat and RTE vegetables)	$NSer_{year} * ri_{eat}$	Cases/year	Calculated
$TNc_{prep+eat}$	Number of cases for all consumers (live chicken, meat and RTE vegetables)	$TNc_{cook} + TNc_{eat}$	Cases/year	Calculated
$TNc_{100,000}$	Total annual number of cases live chicken, meat and RTE vegetables/100,000 persons	(TNC/Rp) *100,000	Cases/year /100,000 persons	Calculated
	DALYs# estimates for chicken consumption (live chicken, meat and RTE vegetables)			
BF_{Sinc}	*Salmonella* spp. incidence associated with poultry meat in Burkina Faso	Constant 76,800	Cases	Havelaar et al., 2022; Year 2017 median estimates for *Salmonella* spp. incidence associated with poultry meat in Burkina Faso
BF_{SDALY}	*Salmonella* spp. DALYs due to poultry meat in Burkina Faso	Constant 34,300	DALYs	Havelaar et al., 2022; Year 2017 median *Salmonella* spp. DALY estimates associated with poultry meat in Burkina Faso
$DALY_{percase}$	DALYs per case of *Salmonella* spp.	BF_{SDALY} / BF_{Sinc}	DALY/Case	Calculated
TDALYs	Total annual number of DALY attributed *Salmonella* from Chicken and vegetable salads	$DALY_{percase} * TNc_{prep+eat}$	DALYs/year	Calculated
$TDALYs_{100,000}$	Total annual number of DALY attributed *Salmonella* from Chicken and vegetable salads per 100,000 persons	(TDALYs/Rp) *100,000	DALY/year /100,000 persons	Calculated

⊕ The study by Dione et al., 2021; provided point average estimates of consumption, in this study we used a pert distribution to account for variability and uncertainty.
⋄ RTE, Ready to eat vegetables.
DALYs, disability adjusted life years.

(Eq. 1) and concentration (Eq. 2) was modelled according to Dogan et al. (2019).

$$P_{i+1} = \frac{P_i \times OR}{1 - P_i + P_i \times OR} \quad (1)$$

where P_{i+1} is the resulting prevalence after a specific slaughter processing step i, P_i is the prevalence before this step i, and OR is the change in prevalence described as an odds ratio.

$$C_{i+1} = C_i + LC \quad (2)$$

where C_{i+1} is the concentration (log_{10}CFU/carcass) after a specific slaughter processing step i, C_i, the initial concentration (log_{10}CFU/carcass) at this step i, and LC the change in log concentration (log_{10}CFU change) due to the activities in that step i (Dogan et al., 2019). Because the slaughter conditions, equipment and environment are not clearly defined to ascertain the means and extend of cross contamination, this study assumed that the log increases and or decreases in microbial concentration on chicken carcass(es) after a particular slaughter processing step is an embodiment of all the possible cross contamination, growth and or inactivation. Concentrations were log transformed for positive carcasses and changes in log concentration (LC) were calculated using the approach of Zwietering et al. (2016).

2.3.3. Carcass transport module

In Burkina Faso, restaurant owners transport chicken carcasses from the marketplace to their restaurants for a duration ranging from 0 to 2 h at a temperature of around 28.6 °C (range 22.5 to 35.6 °C). For both pathogens, it was assumed that there was no inactivation. For *Campylobacter* spp., it was assumed that there was survival and no growth during carcass transport (Pouillot et al., 2012). For *Salmonella* spp., the transport of carcasses can provide an opportunity for growth and for this reason we modelled the growth using a primary (Eq. 3) and secondary (Eq. 4) growth model (Table 1).

$$log_{10}N(t) = log_{10}N_0 + \mu(T) \times t \quad (3)$$

where $N(t)$ is the microbial count on the chicken carcass (CFU/carcass) at time t (hours), N_0 is the initial microbial count (CFU/carcass) and $\mu(T)$ is the growth rate ($\log_{10}$CFU/h) at temperature T (°C). The upper limit of $N(t)$ was set at 1.0×10^8 CFU/cm^2 as the maximum achievable viable cell count (Pouillot et al., 2012) and adjusted to CFU/carcass by incorporating the entire chicken body surface area (Table 1). As in a study in Senegal (Pouillot et al., 2012), a secondary cardinal temperature model (Eq. 4) was used:

$$\mu(T) = 0 \text{ if } T \leq T_{min} \text{ or } T \geq T_{max},$$
$$\mu(T) = \mu_{opt} \times \frac{(T - T_{max})(T - T_{min})^2}{(T_{opt} - T_{min})\left[(T_{opt} - T_{min})(T - T_{opt}) - (T_{opt} - T_{max})(T_{opt} + T_{min} - 2T)\right]} \text{ if } T_{min} < T < T_{max} \quad (4)$$

where $T_{min} = 5.7$ °C is the minimum temperature for growth, $T_{max} = 49.3$ °C is the maximum temperature for growth, $T_{opt} = 40.0$ °C is the optimal temperature for growth, and $\mu_{opt} = 0.7320$ $\log_{10}$CFU/h is the optimal growth rate (Oscar, 2002).

For Ethiopia, neither a live chicken transport module nor a carcass transport module was included in QMRA model for the transport from the market to consumers' homes. This is because, in most cases, only one or two live chicken(s) are transported for slaughter at homes, so the chickens are either contaminated or not and transport of chicken carcasses is very minimal.

2.3.4. Consumer: Restaurant/home module

This restaurant/home module was based on the FAO and WHO (2002) model with modifications. This model was selected to globally capture the complex processes of cross-contamination and undercooking that rise from the many different possible contamination routes and the considerable diversity in the food handling practices of individuals. In this study, we assumed that the whole chicken carcass was prepared, cooked and served together with other RTE foods in a single meal like in the study of Calistri and Giovannini (2008). In their study, Calistri and Giovannini (2008) used a simulation model to quantitatively estimate the expected annual number of human cases of campylobacteriosis due to the cross-contamination during the handling of *Campylobacter jejuni* contaminated chicken meat in the domestic kitchen. The RTE foods refer to fresh vegetables served as fresh salads. In Ethiopia, live chickens are mainly slaughtered at home either directly after they arrive or after holding them for some time and the model uses the same slaughtering processes as at the market in Burkina Faso (Section 2.3.2). Home and restaurant kitchens processes were assumed to be similar and modelled using the same approach.

2.3.4.1. Storage module of chicken carcasses in the kitchen. After slaughter in Ethiopia or arrival of the purchased carcasses at restaurants in Burkina Faso, the storage of chicken carcass was simulated (Table 1 for Burkina Faso). Growth of *Salmonella* spp. during storage at home was modelled in a similar way to the carcass transport model (see Section 2.3.3). In Burkina Faso, storage was at room temperature with a most likely value of 28.6 °C and rang from 22.5 to 35.6 °C as no refrigerators were included in the baseline situation (Dione et al., 2021). In Ethiopia, consumers keep the chicken(s) for 3.4 h (most likely value) with a range from 2.5 h to 5.9 h before slaughter (Dione et al., 2021). For storage of the carcass(es) at homes in Ethiopia, the same temperature and time was used as in Burkina Faso (Appendix C).

2.3.4.2. Cooking module. Adequate cooking of chicken meat most likely destroys all *Salmonella* spp. and *Campylobacter* spp., especially on the surface, however in some parts of the meat, survival may occur. Our cooking module (Route 4, Table 1) was modified from the QMRA model from FAO and WHO (2002) in which a whole chicken was cooked and a proportion of 0.1 to 0.2 of microbial cells on the carcasses were assumed to have a chance of survival. From the FAO and WHO (2002) study, the proportion of the number of pathogens that could survive cooking would be very large, but it was also explained that country specific conditions were not captured in this international study. In our study, cooking practices in Burkina Faso consisted of roasting a cut open and flattened whole carcass (Dione et al., 2021) and in Ethiopia of cutting a carcass into pieces (Amenu et al., 2021), which seriously lower survival changes in the meat. For this reason, the proportion of microbial cells with a chance of survival in the model from FAO and WHO (2002) was divided by a factor of 10 (resulting in a survival proportion of 0.01 to 0.02) for Burkina Faso and of 100 (0.001 to 0.002) for Ethiopia. In addition, this proportion of microbial cells with a chance of survival was also countered by an average of 90 % probability of adequate cooking, meaning that these cells are only important in cases of only 10 % probability of undercooking. Moreover, a sensitivity analysis on the uncertainty of different division factors ranging from 1 to 100 revealed a limited effect on the final number of cases of *Campylobacter* spp. and *Salmonella* spp. (Appendix E, Fig. E.3). Next, a D-value model based on the temperature effect on the decimal reduction times as in Eq. 5.1 for *Salmonella* spp. (FAO and WHO, 2002) and in Eq. 5.2 for *Campylobacter* spp. (Benamar et al., 2021) was used to estimate the number of pathogens surviving the inadequately cooked parts of the chicken meat:

$$D_{Salmonella\ \mathrm{spp.}} = 10^{(-0.139\ T)+8.58} \quad (5.1)$$

$$D_{Campylobacter\ \mathrm{spp.}} = 10^{(-0.16\ T)+9.29} \quad (5.2)$$

where the D is the time (minutes) for a 90 % reduction in the numbers of pathogens at a given temperature and T (°C) is the temperature of exposure of pathogens in undercooked meat portions.

2.3.4.3. Cross-contamination module. Table 1, Appendix A, B, and C detail the inputs for the cross-contamination module in a restaurant/consumer kitchen in the two countries and for both pathogens. Our cross-contamination module was based on the QMRA model from FAO and WHO (2002) with modifications. The FAO and WHO (2002) model considered an average of 10 % transfer rate for direct and indirect cross-contamination of pathogenic cells between contact surfaces. In our study, transfer rates were obtained from different studies (Verhoeff-Bakkenes et al., 2008; Luber et al., 2006; Rusin et al., 2002) and were applied as proportions like in the FAO and WHO (2002) model. In addition, our cross-contamination module also added the human behavior of touching lips. The module assumes that only loosely attached pathogenic cells are involved in cross-contamination, similar to the approach of the drip fluid model (FAO and WHO, 2009). It was assumed that live chickens or chicken meat were the sole sources of *Salmonella* spp. or *Campylobacter* spp. in the kitchen (hands of cooks and utensils) and RTE were contaminated at the time of serving, so no growth models of *Salmonella* spp. on surfaces of hands, kitchen utensils and RTE were included in our study. Fig. 1 shows the cross-contamination routes in Burkina Faso and Ethiopia through which these pathogens can be ingested by humans. For Ethiopia, an extra route (Route 0) was modelled from consumers handling live chickens during home slaughter and thereafter touching the lips. The transfer of pathogens from live chickens or from raw chicken meat to the hands was followed by transfer from hands to lips (Table 1). The number of *Salmonella* spp. and *Campylobacter* spp. on chicken meat or live chickens and the proportion transferred determines the numbers transferred to kitchen utensils and hands, thereafter to cooked chicken meat, RTE or lips, and finally to ingestion. The study assumed that after cross contamination of RTE, the meals are served without waiting time to allow growth of *Salmonella* spp. on RTE. Having contaminated hands does not necessarily translate into transferring the pathogens to lips, so a probability of touching the lips was incorporated. It was assumed that hand washing would remove all the pathogens on the hands.

2.3.5. Exposure assessment outputs

At the end of the exposure assessment, the total number of cells (dose) of *Salmonella* spp. or *Campylobacter* spp. consumed per serving was obtained for each transmission route in addition to determining their respective probability of exposure (Table 1). To estimate the dose per serving for each route, the total number of cells (CFU) in a meal (whole cooked chicken and contaminated batch of fresh salad) was divided by the average number of persons who consumed the meal (Table 1), assuming equal distribution of pathogenic cells in serving portions (FAO and WHO, 2002). In Burkina Faso, the number of persons consuming a meal with chicken meat was obtained in a field study in a related project work package (average 3 persons/chicken), while in Ethiopia, the number of people in a household (average 5 persons/chicken) (DHS-Ethiopia, 2016) was used. For each route, the probability of exposure through that route was calculated from the final prevalence after slaughtering and washing and the probability of the route to occur.

2.4. Hazard characterization

In hazard characterization, the total number of cells (dose) of *Salmonella* spp. and *Campylobacter* spp. consumed per serving from the exposure assessment were used as input in the dose-response model to determine the probability of infection given a dose per route. Improvement of existing dose-response models is ongoing (Teunis, 2022) and the choice of what model to use remains contentious. For this study, a beta-Poisson model (Eq. 6) was used for both *Salmonella* spp. and *Campylobacter* spp. to describe the dose-response relationship, because this model has been used in globally accepted studies (FAO and WHO, 2002, 2009).

$$P_{infecD} = 1 - (1 - r_{dose})^{D} \tag{6}$$

where P_{infecD} is the probability of infection given a dose, D the number of cells (dose) of *Salmonella* spp. or *Campylobacter* spp. consumed per serving, and r_{dose} the probability of infection from consuming a single cell with a distribution of Risk Beta (0.1324, 51.45) for *Salmonella* spp. (FAO and WHO, 2002) and Risk Beta (0.21, 59.95) for *Campylobacter* spp. (FAO and WHO, 2009).

For *Salmonella* spp., the probability of illness given a contaminated serving (P_{ill}) was assumed to be equal to the probability of infection given a dose (P_{infecD}) (FAO and WHO, 2002). For *Campylobacter* spp., the conditional probability in Eq. 7 was used (FAO and WHO, 2009):

$$P_{ill} = P_{infecD} \times P_{ill,inf} \tag{7}$$

where $P_{ill,inf}$ is the dose-independent conditional probability of getting ill given infection and a beta distribution, RiskBeta (30, 61) was used (FAO and WHO, 2009).

2.5. Risk characterization

In the risk characterization step, we integrated the probability of exposure for each route from the exposure assessment (Section 2.3) and the probability of illness given a contaminated serving from hazard characterization (Section 2.4) to generate the risk per serving for each transmission route, the overall risk per serving, and the estimates of the number of cases and DALYs of campylobacteriosis and salmonellosis associated with the preparation and consumption of chicken meat served together with RTE vegetables in Burkina Faso and Ethiopia.

2.5.1. Risk per serving

The risk per serving for each route was calculated by multiplying the respective probability of illness given a contaminated serving with the probability of exposure (Table 1). The individuals at risk were proportioned into two groups, those who cook and eat (cooks) and those who do not cook but only eat, because these individuals were assumed to be exposed differently. For cooks, all routes (0 to 6 in Ethiopia, 1 to 6 in Burkina Faso) were included, while for those who only eat, route 0 and 2 in Ethiopia and route 2 in Burkina Faso were excluded (Fig. 1 and Table 1). For each risk group, the respective overall risk per serving was computed by subtracting the product of no risk (i.e., one minus risk per serving) for all the applicable transmission routes from the maximum attainable probability value (one) as shown in Table 1.

2.5.2. Risk estimates at population level

The arithmetic means of the overall risk per serving from the two risk groups in Section 2.5.1 were used as inputs for the risk at population level, following the approach employed by Benamar et al. (2021). Thirty random simulations with each 1,000,000 iterations showed that the arithmetic mean of the overall risk per serving did hardly differ between simulations (standard deviation <0.005 times the mean). It should be noted that the variability in the outcome is very small, due to the very large numbers of servings consumed (multiple millions). However, the arithmetic mean itself is largely influenced by the variability of input parameters, since this mean is largely influenced by a long right tail in the risk per serving. For risk at population level, the number of cases for each risk population group (cooks and those who do not cook) and the associated DALYs were calculated. The arithmetic mean of the overall risk per serving was multiplied by the number of servings of chicken meat with RTE per year. To obtain the number of servings, the number of persons in the risk population for either the cooks or those who only eat was multiplied by the weighted average annual frequency of chicken meat consumption. Risk populations were determined by subtracting the estimated number of cooks in each country from the entire population to obtain number of persons who only eat. In Burkina Faso, the ratio of cooks to customers served per day in street restaurants where chicken meat is served was multiplied with entire country population to obtain the population of cooks (Table 1 and Appendix A). In Ethiopia, the average family size was used and assumed that one family member takes on the role of a cook at a time and this fraction was multiplied by the entire population to obtain the number of cooks (Appendix B and C). In addition, field studies in Burkina Faso (Dione et al., 2021) and

Ethiopia (Amenu et al., 2021) also showed that the consumption of chicken meat depended on income level (low, middle, and high). The fraction of persons in each income category and the income category dependent consumption level was used to calculate the weighted average annual frequency of chicken meat consumption (Table 1). For Ethiopia, we also considered the impact of religious fasting on the frequency of chicken meat consumption (Ethiopian orthodox.org, 2022) that reduced the consumption year to <12 months (Appendix B; C).

The total number of cases per year were the sum of the annual cases in the cooks' risk population and those cases of individuals who only consumed chicken meat. Finally, we calculated the DALYs per year by multiplying the number of cases by the number of DALY per case for each pathogen in a country. The DALY per case estimates were obtained by dividing the burden of foodborne disease (DALYs) by the number of cases caused by selected pathogens in Burkina Faso and Ethiopia, which were both retrieved from the study of Havelaar et al. (2022) that estimated the burden of foodborne disease due to bacterial hazards associated with beef, dairy, poultry meat, and vegetables in Ethiopia and Burkina Faso.

2.6. Sensitivity analysis

Model sensitivity analysis was conducted based on Spearman's rank correlation coefficient in @Risk software to identify the model inputs whose provided variability correlated most with the variability in the output (overall risk per serving). The overall risk per serving for cooks was used for this purpose because it captured all the transmission routes. Model inputs with high correlation can provide an indication of where candidate food safety intervention can be allocated. Because such model inputs were found in all steps of the chicken meat supply chain, candidate intervention scenarios were selected in each step of the supply chain.

2.7. Intervention scenarios

To select candidate intervention scenarios to include in our study that are realistic for the local settings (Table 2), project meetings were organised with local people in Burkina Faso (Dione et al., 2021) and Ethiopia (Amenu et al., 2021). Candidate intervention scenarios were simulated as alternatives to the baseline models in what-if scenarios (Table 2). Like in most risk assessment studies (Collineau et al., 2020b; Dogan et al., 2019; Signorini et al., 2013; Nauta et al., 2005b; FAO and WHO, 2002), our study is also based on the notion that the true utility of the baseline model lies in its ability to provide a basis to assess relative changes in risk outcomes when intervention scenarios are introduced (Collineau et al., 2020b). Input data about the efficacy of these candidate intervention scenarios were obtained from literature (Table 2), with a preference for data from real life farming and slaughter systems, and practices rather than from laboratory-based studies. In case there were no studies, a 50 % risk reduction target was applied like in the study of Smadi and Sargeant (2013). Different intervention implementation targets (25 %, 50 %, 75 %) to reduce the risk of pathogens were tested to evaluate the uncertainty of the set target of the intervention. Efficacy of each candidate intervention implementation target compared to the baseline was determined in relative reduction in number of cases (Eq. 8) (Dogan et al., 2019) and as avoided DALYs by subtracting the DALYS after implementing an intervention scenario from the DALYs in the baseline situation without the intervention scenario.

$$\%\text{Relative reduction in number of cases} = \frac{Nc_{baseline} - Nc_{intervention}}{Nc_{baseline}} \times 100 \tag{8}$$

where $Nc_{baseline}$ and $Nc_{intervention}$ refer to the annual number of cases of campylobacteriosis and salmonellosis in a country from the baseline and the candidate intervention scenario, respectively.

Table 2
Descriptive summary of the baseline quantitative microbial risk assessment model for *Campylobacter* spp. and *Salmonella* spp. and candidate intervention scenarios for the chicken supply chain ("farm to fork") in Burkina Faso and Ethiopia.

		Assumptions∗
Baseline		Baseline models were developed for the predominant chicken meat supply chain routes in each country, assuming that the vast majority of microbial risk of chicken meat consumption and preparation would come from those supply chains. **Burkina Faso** Small scale village farming systems of 5 to 50 chickens — live chicken transport — live market selling and market slaughter — carcass transport — roadside restaurants — consumption (Dione et al., 2021). **Ethiopia** Small scale village farming systems of 5 to 50 chickens — live chicken transport — live market selling — live chicken transport — home slaughter and cooking —consumption (Amenu et al., 2021).
Candidate intervention scenarios at different stages of the supply chain		**Changes from the baseline model:**
Farm		
1	Improve biosecurity by changing to intensive farming system ‡	Improved biosecurity measures (chicken house, easy to clean feeders and drinkers, foot bath and clean drinking water) reduced prevalence of pathogens in the baseline model by 50 %.
2	Feed and water additives: Probiotics	Application of probiotics through feed or water reduced the concentration of *Campylobacter* spp. and *Salmonella* spp. in feces with a Log change of Risk Pert (0.55, 1, 2.81) (Saint-Cyr et al., 2016; Santini et al., 2010; Guyard-Nicodème et al., 2017) and Risk Pert (0.2, 0.5, 1.5) (Wang et al., 2011; Chambers and Lu, 2002; Wang et al., 2011), respectively.
3	Feed and water additives: Plants extracts	Application of plant extracts through feed or water reduced the concentration of *Campylobacter* spp. and *Salmonella* spp. in feces with a Log change of Risk Pert (0, 0.56, 2.05) (Arsi, 2014) and Risk Uniform (0, 2.0) (Varmuzova et al., 2015), respectively.
4	Feed and water additives: Organic acid blends	Application of probiotics through feed or water reduced the concentration of *Campylobacter* spp. and *Salmonella* spp. in feces with a Log change of Risk Pert (3, 3.5, 4) (de Los Santos et al., 2008) and Risk Pert (0.4, 1, 2.5) (Koyuncu et al., 2013; Sultan et al., 2015), respectively.
5	Vaccination	Application of vaccine reduced the concentration of *Salmonella* spp. with Risk Pert (0.36, 1.43, 2.5) (Bailey et al., 2007; Buckley et al., 2010; Guo et al., 2019; Okamura et al., 2012; Piao et al., 2007). By the time of our study, no commercial vaccine for *Campylobacter* spp. was available.
Transport of live birds		
6	Improved transport conditions of live birds	Live birds are transported with limited stress and stacked in a way to avoid spread of fecal dropping from one bird to another, reducing the increase in concentration and

(continued on next page)

Table 2 (*continued*)

		Assumptions*
		prevalence due to transport from the baseline model by 50 %.
Market		
7	Avoid cross contamination between live birds at market	Live birds at market are kept in separate battery cages and birds do not step in fecal droppings, continuous cleaning of the cage floor. It was assumed that the spread and increase of *Campylobacter* spp. and *Salmonella* spp. (prevalence and concentration) at market was reduced by 50 %
8	Good hygienic slaughter practices ‡	Slaughter places are equipped with equipment and personnel that promote good hygienic conditions viz; stainless steel killing cones to avoid flapping of wings, blood collection vessels to avoid uncontrolled spread and splashing, designated knives, clean water, easy to clean contact surfaces and hanging equipment. Increase in concentration and prevalence due to slaughter processes was reduced by 50 % and the effect of carcass washing increased by 50 % in the baseline model.
9	Improved carcass washing at slaughter	Slaughter places have enough running potable water. The reduction of microbial concentration due to carcass washing was increased by 50 %.
Transport of carcasses		
10	Improved carcass transport from market to restaurants	**Burkina Faso** Carcasses are transported in cooling boxes. It was assumed that the growth rate of *Salmonella* spp. was reduced by 50 %. The intervention was not applied for *Campylobacter* spp. **Ethiopia** This scenario was not simulated because in the study area, most of the slaughter occurs at home. The intervention is not applicable.
Home/ Restaurants		
11	Improved hand washing after handling live and slaughtered chicken	Food handlers in homes and restaurants have enough hand washing facilities and running potable water. The probability that hands are not washed was reduced by 50 % and accordingly applied to the contribution of cross contamination from hands and touching the lips during chicken holding and preparation at restaurant/home.
12	Refrigeration	Homes/restaurants are equipped with refrigerators for storing slaughtered chicken carcasses during holding. For *Campylobacter* spp., review on studies indicate that air cooling resulted in a reduction in concentration of 0.1 to 1 log (Rasschaert et al., 2020) and a hence a Risk Pert (0.1, 0.55, 1) distribution was deducted from the baseline model. For *Salmonella* spp. it was assumed that the growth rate was reduced by 50 % at home/restaurant.
13	Freezing	Homes/restaurants are equipped with freezers for storing slaughtered chicken carcasses during holding. For *Campylobacter* spp., after one day of freezing at −18 °C is expected to reduce the concentration by 1 to 2.4 log (Rasschaert et al., 2020) and hence a Risk Pert (1, 1.7, 2.4) distribution was deducted from the baseline model. For *Salmonella* spp. it was assumed that no growth at holding and hence removed the growth module at home/restaurant and assumed no inactivation.
14	Designated utensils	Food handlers use separate work surfaces for raw chicken, RTE and cooked chicken, thereby reducing concentration by 50 %. Current probability of using the same cutting boards and utensils was decreased by 50 % at home/street restaurant.
15	Improved cooking/roasting	Food handlers get the resources and also change in behavior to improve on chicken cooking/roasting. Effect of undercooking (probability of under cooking) at home/street restaurant was lowered by 50 %.
16	Combined efforts at restaurant/ home (Scenario 11 + 14 + 15)	We deducted from the baseline model the intervention of improved hand washing behaviors (11), combined effect of using designated utensils (14), and improved cooking (15). Refrigeration or freezing was not included because implementation of refrigeration or freezing in restaurants was not seen as feasible in practice due to the lack of electricity infrastructure. In a recent study, <40 % of the respondents had freezers and refrigerators (Assefa et al., 2023). For Ethiopia, the intervention of hygienic slaughter (8) was also included.
Combined interventions at different steps of the supply chain		
17	Combined interventions at market and at home/restaurants (Scenario 8+ 11 + 14 + 15)	**Burkina Faso** Based on the current situation, the chicken markets and restaurants are characterized with key steps and activities that can visibly lead to contamination and cross-contamination. Consequently, we deducted from the baseline model a combined effect of hygienic slaughter (8), improved hand washing behaviors (11), using designated utensils (14), and effective cooking (15). Refrigeration or freezing was not included because implementation of refrigeration or freezing in restaurants was not seen as feasible in practice due to the lack of electricity infrastructure. **Ethiopia** This scenario was not simulated because in the study area, there are limited activities at market most of the slaughter occurs at home. The intervention would not be feasible.

* If two countries (Burkina Faso and Ethiopia) are mentioned, assumptions differ between countries. If one country is indicated, it implies that the assumptions only apply to that country and not to the other. If no country is indicated, the assumptions are the same for both countries. If no data was available on the efficacy of a particular intervention, a 50 % reduction was assumed (Smadi and Sargeant, 2013).

‡ Multiple action interventions; these scenarios involve combining food safety actions in one supply chain step.

Statistical analysis was conducted to investigate if there was a significant difference between the relative risk after implementing the different intervention scenarios and for comparing the risk reduction targets of 25 %, 50 % and 75 %. Values for the number of cases of *Campylobacter* spp. and *Salmonella* spp. generated from the probability density output in @Risk software were analyzed using one way analysis of variation (ANOVA) in SPSS (version 28, IBM, New York, USA) with

Table 3
Overall risk of illness per serving of chicken meat for individuals who cook and eat and those who individuals who only eat without participating in the cooking in Burkina Faso and Ethiopia.

Overall risk per serving*	Individuals who cook and eat						Individuals who only eat without cooking					
	Mean	Minimum	2.5th#	Median	97.5th #	Maximum	Mean	Minimum	2.5th #	Median	97.5th #	Maximum
Campylobacter spp. Burkina Faso	3.91×10^{-3}	0	0	1.05×10^{-7}	2.12×10^{-2}	1.90×10^{-1}	3.74×10^{-3}	0	0	9.83×10^{-8}	2.07×10^{-2}	1.44×10^{-1}
Campylobacter spp. Ethiopia	2.52×10^{-2}	0	0	5.84×10^{-5}	1.44×10^{-1}	4.20×10^{-1}	2.03×10^{-2}	0	0	2.41×10^{-5}	1.20×10^{-1}	3.52×10^{-1}
Salmonella spp. Burkina Faso	1.61×10^{-3}	0	0	3.84×10^{-9}	8.3×10^{-3}	3.46×10^{-1}	1.57×10^{-3}	0	0	3.76×10^{-9}	8.1×10^{-3}	2.91×10^{-1}
Salmonella spp. Ethiopia	1.08×10^{-2}	0	0	5.64×10^{-8}	1.41×10^{-1}	6.85×10^{-1}	7.67×10^{-3}	0	0	3.26×10^{-8}	1.04×10^{-1}	6.09×10^{-1}

* Overall risk per serving is a function of the probability of illness given a contaminated serving and the probability of exposure to either *Campylobacter* spp. and *Salmonella* spp.
# Percentiles.

0.05 level of significance and Tukey's post hoc tests.

3. Results and discussion

3.1. Risk estimates from baseline models

Table 3 shows the estimates of the overall risk of campylobacteriosis and salmonellosis per serving for the cooks and those individuals who only eat chicken meat with ready-to-eat vegetables in Burkina Faso and Ethiopia. In Burkina Faso, the baseline models predicted on average an overall risk of 391 illnesses per 100,000 servings due to *Campylobacter* spp. for cooks and 374 for persons who only eat. In Ethiopia, this was 2520 illnesses per 100,000 servings for cooks and 2030 for persons who only eat. For *Salmonella* spp., in Burkina Faso average overall risk was 161 illnesses per 100,000 servings for cooks and 157 for persons who only eat, and in Ethiopia 1080 and 767. These results for both countries need to be interpreted with caution as for some model inputs we used surrogate data and data from other countries where data from Burkina Faso and Ethiopia could not be found. Nevertheless, the QMRA model framework and the risk estimates provided in this study have helped to

Table 4
Number of foodborne disease cases and disability adjusted years (DALY) per 100,000 persons per year due to *Campylobacter* ssp. in chicken meat in Burkina Faso and Ethiopia in the baseline model and effectiveness of candidate intervention scenarios in the chicken meat supply chain.

	No. of cases per year/ 100,000 persons		DALYs per year /100,000 persons⋇		Risk reduction⊕	
	Burkina Faso	Ethiopia	Burkina Faso	Ethiopia	Burkina Faso	Ethiopia
	Mean	Mean	Mean	Mean		
Baseline	6482	12,145	164	272	——	——
Candidate intervention scenarios						
Farm						
1. Improve biosecurity by changing to intensive farming system‡	2692	5675	68	127	58 %	53 %
2. Feed and water additives: Probiotics	5641	10,936	143	245	13 %	10 %
3. Feed and water additives: Plant extracts	5927	11,283	150	253	9 %	7 %
4. Feed and water additives: Organic acids	5189	10,266	131	230	20 %	15 %
5. Vaccination		**	**	**	**	**
Transport of live birds						
6. Improved transport conditions of live birds	4430	9404	112	211	32 %	23 %
Market						
7. Avoid cross contamination between live birds at market	4244	8851	107	198	35 %	27 %
8. Good hygienic slaughter practices#‡	1357[a]	3079[a]	34	69	79 %	75 %
9. Improved carcass washing at slaughter#	5839	10,875	148	244	10 %	10 %
Transport of carcasses						
10. Improved carcass transport from market to restaurants	**	**	**	**	**	**
Home/ Restaurants						
11. Improved hand washing after handling live and slaughtered chicken	5239	7775	133	174	19 %	36 %
12. Refrigeration	5511	9374	140	210	15 %	23 %
13. Freezing	2919	4860[a]	74	109	55 %	60 %
14. Designated utensils	2952	7601	75	170	54 %	37 %
15. Improved cooking/roasting	6351	12,121	161	272	2 %	0.2 %
16. Combined efforts at restaurant/home (Scenario 11+ 14 + 15)	1614[a]	777[a]	41	17	75 %	94 %
Combined interventions at different steps of the supply chain						
17. Combined interventions at market and at home/restaurants (Scenario 8 + 11+ 14 + 15)	341[a]	**	9	**	95 %	**

For Ethiopia, these steps mainly occur at home.
⊕ Risk reduction was calculated by dividing the difference of the mean number of illnesses in the baseline and each hypothetical intervention scenario with the baseline mean number of illnesses multiplied by 100.
** Intervention scenario was not deemed feasible for the Ethiopia chicken meat supply chain.
⋇ DALYs per year /100,000 persons were calculated by multiplying the number of cases by the DALYs per case (0.447 for Burkina Faso and 0.0911 for Ethiopia) in Table 1 and Appendix C as derived from the study of Havelaar et al. (2022).
‡ Multiple action interventions; these scenarios involve combining food safety actions in one supply chain step.
a Differences in relative risk for interventions with this superscript letter for a given country are not statistically significant.

identify the most important data gaps, and can be used to direct QMRA data collection and to provide a benchmark for future studies in Africa.

Table 3 also shows estimates of the median, minimum, maximum, 2.5th, and 97.5th percentile for the overall risk per serving. The estimates for the overall risk per serving were left skewed with a great proportion of zero values (minimum and 2.5th percentile), and a long right tail leading to high values with very low chance of occurrence. Zero values of the minimum and the 2.5th percentile resulted from the zero % prevalence of the pathogen on the chicken, meaning that if the pathogen is not present on chicken there is no risk in a serving. The long right-hand tail results from combinations of non-linear effects such as the effect of temperature on growth rate (quadratic) and exponential growth, resulting in large effects of the combination of higher temperature and time on the number of cells and the risk per serving. These 2.5 and 97.5th percentiles should not be simply multiplied with the number of servings, since that would incorrectly assume that all servings would be all either at the lower or at the higher risk level. In reality, with every serving we are sampling from this probability distribution. With the very large number of servings consumed, the number of cases has largely lower variability and follows the central limit theory. Such an effect was also shown recently by Stathas et al. (2024) where the risk per serving for chicken patties varied largely, namely from 0 to 0.105, while the number of cases varied with less than a factor 10 (from 0.96 to 6.59 cases per 100,000 people). Consequently, we presented the next results as arithmetic means as also done by Benamar et al. (2021), to show the impact of different interventions as it is more representative of the risk distribution (Table 4 and 5).

Table 4 shows that in the baseline situation the estimated mean annual number of cases of campylobacteriosis per 100,000 persons associated with chicken meat consumption and preparation was 6482 in Burkina Faso and 12,145 in Ethiopia, resulting in a mean of 164 and 272 DALYs per 100,000 persons per year, respectively. Table 5 shows that the estimated mean annual number of cases of salmonellosis per 100,000 persons associated with chicken meat consumption and preparation was 2713 in Burkina Faso and 4745 in Ethiopia, resulting in a mean of 1212 and 432 DALYs per 100,000 persons per year, respectively.

For both pathogens, the overall risk per serving and thereafter the number of cases per 100,000 persons in Ethiopia were higher compared to Burkina Faso by a factor of 6.5 and 2, respectively, because of the structural difference in the chicken meat supply chain (Fig. 1). In Ethiopia, the slaughtering of live chickens at home may introduce higher pathogen load to cooks and consumers, thereby increasing the risk of cross contamination and the number of cases. From Table 5, it can also be observed that the annual number of cases per 100,000 persons due to *Salmonella* spp. in Ethiopia were approximately 2 times higher than in Burkina Faso, but the DALY burden was the reverse by approximately 3 times. This originates from the difference between the countries in the number of DALY per case as derived from the data in Havelaar et al. (2022) (Burkina Faso 0.448 DALY/case, 400 cases and 179 DALYs per

Table 5
Number of foodborne disease cases and disability adjusted years (DALY) per 100,000 persons per year due to *Salmonella* ssp. in chicken meat in Burkina Faso and Ethiopia in the baseline model and effectiveness of candidate intervention scenarios in the chicken meat supply chain.

	No. of cases per year/ 100,000 persons		DALYs per year /100,000 persons[Ж]		Risk reduction[⊕]	
	Burkina Faso	Ethiopia	Burkina Faso	Ethiopia	Burkina Faso	Ethiopia
	Mean	Mean	Mean	Mean		
Baseline	2713	4745	1212	432	— —	— —
Candidate intervention scenarios						
Farm						
1. Improve biosecurity by changing to intensive farming system‡	1092[a]	1765[a]	488	161	60 %	63 %
2. Feed and water additives: Probiotics	2517	4299	1124	392	7 %	9 %
3. Feed and water additives: Plant extracts	2461	4187	1099	382	9 %	12 %
4. Feed and water additives: Organic acids	2439	4065	1089	370	10 %	14 %
5. Vaccination	2398	4003	1071	365	12 %	16 %
Transport of live birds						
6. Improved transport conditions of live birds	1921	3264	858	297	29 %	31 %
Market						
7. Avoid cross contamination between live birds at market	1668	1823[a]	745	166	39 %	62 %
8. Good hygienic slaughter practices#‡	933[a]	1351[a]	417	123	66 %	72 %
9. Improved carcass washing at slaughter#	2057	3133	919	286	24 %	34 %
Transport of carcasses						
10. Improved carcass transport from market to restaurants	2204	**	985	**	19 %	**
Home/ Restaurants						
11. Improved hand washing after handling live and slaughtered chicken	2520	3170	1125	289	7 %	33 %
12. Refrigeration	1175	1724[a]	525	157	57 %	64 %
13. Freezing	375[a]	616[a]	167	56	86 %	87 %
14. Designated utensils	1376	2864	614	261	49 %	40 %
15. Improved cooking/roasting	2248	4671	1004	426	17 %	2 %
16. Combined efforts at restaurant/home (Scenario 11+ 14 + 15)	689[a]	331[a]	308	30	75 %	93 %
Combined interventions at different steps of the supply chain						
17. Combined interventions at market and at home/restaurants (Scenario 8 + 11+ 14 + 15)	237[a]	**	106	**	91 %	**

[#] For Ethiopia, these steps mainly occur at home.
[⊕] Risk reduction was calculated by dividing the difference of the mean number of illnesses in the baseline and each hypothetical intervention scenario with the baseline mean number of illnesses multiplied by 100.
[**] Intervention scenario was not deemed feasible for the Ethiopia chicken meat supply chain.
[Ж] DALYs per year /100,000 persons were calculated by multiplying the number of cases by the DALYs per case (0.447 for Burkina Faso and 0.0911 for Ethiopia) in Table 1 and Appendix C as derived from the study of Havelaar et al. (2022).
[‡] Multiple action interventions; these scenarios involve combining food safety actions in one supply chain step.
[a] Differences in relative risk for interventions with this superscript letter for a given country are not statistically significant.

100,000 persons per year; Ethiopia 0.091 DALY/case, 360 cases and 32.8 DALYs per 100,000 persons per year), due to a higher prevalence of the much more severe invasive non-typhoidal *Salmonella* in Burkina Faso than in Ethiopia (IMHE, 2019). In addition, the number of cases due to *Campylobacter* spp. in Burkina Faso were approximately 2 times higher than those due to *Salmonella* spp., but the DALY burden due to *Salmonella* spp. was approximately 7 times higher than those due to *Campylobacter* spp. The same trend was observed for Ethiopia, only that the DALY burden of *Salmonella* spp. was approximately 2 times higher. This trend reveals that *Campylobacter* spp. had a higher number of cases but *Salmonella* spp. led to higher morbidity and mortality and DALYs (Havelaar et al., 2022). To put our results in context, we compared our risk estimates with comparable studies from Burkina Faso and Ethiopia. Havelaar et al. (2022) reported 1710 cases/100,000 persons/year and 43.3 DALYs/100,000 persons/year due to *Campylobacter* spp. associated with poultry meat consumption in Burkina Faso for the data reference year of 2017. *Salmonella* spp. estimates were 400 cases and 179 DALYs (Havelaar et al., 2022). In Ethiopia, 1340 cases and 29.9 DALYs due to *Campylobacter* spp. and *Salmonella* spp. estimates were 360 cases and 32.8 DALYs due to poultry (Havelaar et al., 2022). Overall, the estimates in this study for *Campylobacter* spp. and *Salmonella* spp. were approximately 4 and 7 times higher than that of Havelaar et al. (2022) in Burkina Faso, and 9 and 13 times higher in Ethiopia, respectively. Although relevant, it is difficult to compare our study to other studies due to the differences in study approach and methodology, and level of food safety control and measures in different countries. In this study, we employed the bottom-up risk assessment approach on food supply chain data, while in the study of Havelaar et al. (2022), a top-down risk assessment approach (based on epidemiological data) was applied. Bottom-up estimates can be higher than top-down (Gkogka et al., 2013), due to for example fail-safe assumptions and effect of immunity. Other studies (Godínez-Oviedo et al., 2022: Collineau et al., 2020b; Dogan et al., 2019; Brynestad et al., 2008) applied a bottom-up methodology similar to our study. The higher estimates in our study may be attributed to the difference in food safety conditions such as (assumed) level of implementation of HACCP systems along the chicken meat supply chain. Furthermore, in our study we included not only chicken meat but also RTE fresh salad and cooks' behavior of touching lips in our model, and these additional pathways were not included in these other studies.

3.2. Microbial transmission routes

Fig. 2 shows the ingested dose (number of cells of pathogens at consumption in case of contamination) for each pathogen transmission route, the probability of exposure, and the expected ingested dose calculated as the product of the ingested dose and the probability of exposure for each transmission route. For both *Campylobacter* spp. and *Salmonella* spp. in Burkina Faso and Ethiopia, most transmission routes showed expected ingested doses in a same order of magnitude. However, for *Campylobacter* spp. route 4 (survival due to undercooking) was lower than for *Salmonella* spp. in both countries, because *Campylobacter* spp. is more sensitive to heat compared to *Salmonella* spp. as shown in Eq. 5.1 and 5.2. Additionally, route 0 in Ethiopia (cooks touching the live chickens at home) on average had a microbial count of 2 $\log_{10}$CFU higher than all the other routes for both pathogens, because of the high pathogen load on live chickens. Noteworthy, if the doses are still in the linear part of the dose-response equation (Eq. 6), so before the first curvature of the dose-response correlation, the dose multiplied with the probability of exposure of a route would be proportional to the contribution of that route (Fig. 2). Since most routes contribute about equally to the risks, there is not one standing out intervention on a specific route that would be most effective. This means that, even though an intervention might be very effective in reducing the impact of a certain route, the contribution of the other non-targeted routes will prevent the overall risk to be reduced much by that intervention. Although route 0 for Ethiopia is a little larger (so interventions in this route seem to be most effective), it is important to note that at this stage the probability of being a cook is not included. Route 4 is lower for *Campylobacter* spp. in

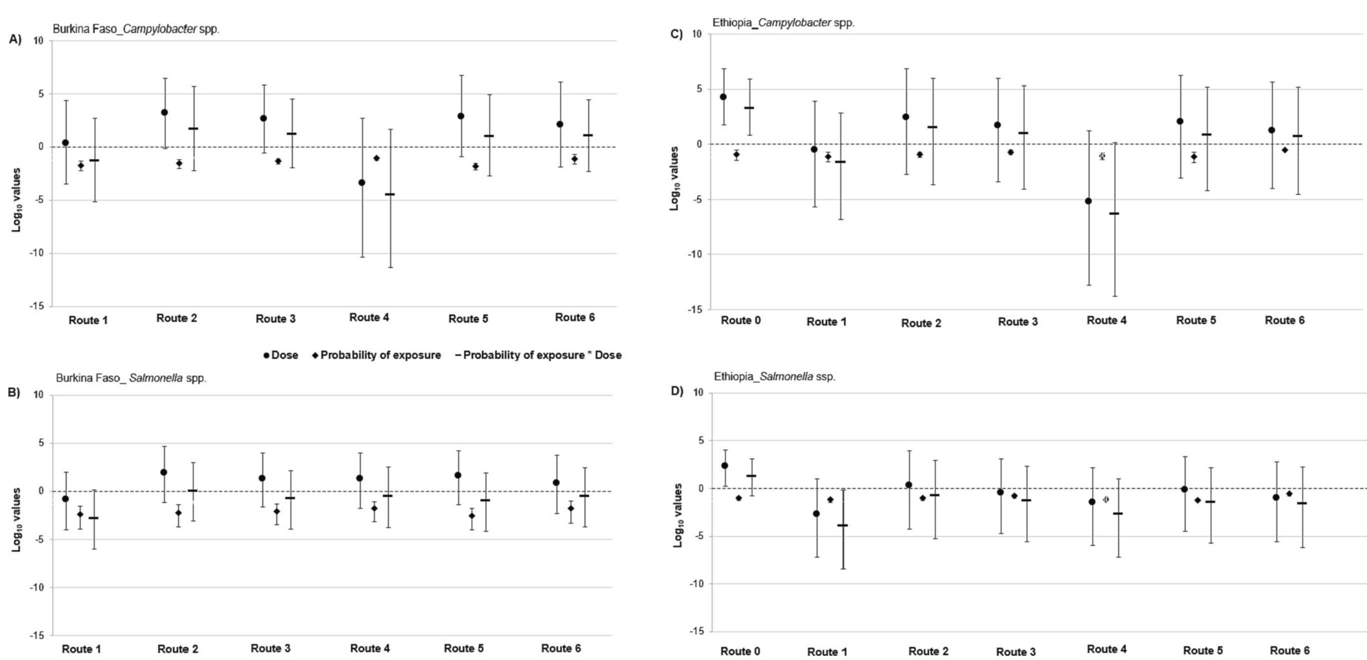

Fig. 2. Estimates of *Campylobacter* spp. and *Salmonella* spp. dose in CFU (number of cells in colony forming units) after exposure assessment for each transmission route, probability of exposure for each route and the expected ingested dose for each route (dose* probability of exposure) associated with chicken meat and ready to eat vegetables preparation in Burkina Faso (Panel A and B) and Ethiopia (Panel C and D respectively). Whiskers represent the lower and higher values of the 2.5th and 97.5th percentile showing variability and uncertainty. Route 0: Live chickens — hands — touching lips — ingestion (in Ethiopia only). 1: Carcass — hands — cold ready-to-eat foods — ingestion. 2: Carcass — hands — touching lips — ingestion. 3: Carcass — cutting boards and other utensils — cold ready-to-eat foods — ingestion. 4: Carcass — undercooked chicken meat — ingestion. 5: Carcass — cutting boards and other utensils — cooked chicken meat — ingestion. 6: Carcass — hands — cooked chicken meat — ingestion.

both countries and for *Salmonella* spp. in Ethiopia, so better cooking is not effective in reducing the risk, while the dose for *Salmonella* spp. in Burkina Faso (Fig. 2B) is more in the similar range as the other routes and some effect of improved cooking is seen in Table 5 (17 % reduction, while no relevant effect for *Campylobacter* was seen; Table 4).

We also explored separately the public health impact in Ethiopia of only consumption of chicken meat with RTE salads, i.e., if routes 0 and 2 in which cooks ingest pathogens from contaminated hands were excluded. This would reduce the annual number of cases of *Campylobacter* spp. and *Salmonella* spp. by 18 % and 29 % in the cooks population and by 5 % and 7 % in the entire population in Ethiopia, respectively. Although Route 0 and 2 in Ethiopia (Fig. 2) have the highest dose, this dose is countered by the associated probability of exposure that is not significantly different from the other routes and the fact that the cooks are just a fraction of all people, making all the transmission routes significant to evoke food safety action.

3.3. Model sensitivity analysis

Fig. 3 shows tornado plots with the first 10 model inputs whose variation gave the greatest variation in the risk per serving due to *Campylobacter* spp. and *Salmonella* spp. in the baseline model for both countries. In both countries, cross-contamination through using the same utensils (cutting board, knifes) for cooked chicken or RTE fresh salad and raw chicken (i.e., probability of same utensils used for carcass and RTE in Fig. 3) is very important. In Burkina Faso, the top model input was the probability that the same utensils are used for both cooked chicken or RTE fresh salad and raw chicken meat in both the *Campylobacter* spp. and *Salmonella* spp. baseline model. For Ethiopia, the model input on the behavior of not washing hands by cooks during chicken and RTE preparations (i.e., hands not washed after carcass at home in Fig. 3) came first in one of the baseline models and third in the other. However, Fig. 3 also shows that the risk per serving due to *Campylobacter* spp. and *Salmonella* spp. were influenced by model inputs from all steps of the chicken meat supply chain apart from transport of live chickens and chicken meat. A link between supply chain steps and the variation in the overall risk per serving was also drawn. For Burkina Faso, five out of the nine supply chain related inputs (not including dose response model parameters) that caused the highest variation in the risk per serving due to *Campylobacter* spp. were at market step of the supply chain, while the remaining four out of the nine were at restaurant step and none was at farm step (Fig. 3). For *Salmonella* spp. in Burkina Faso, of the nine supply chain related inputs that caused the highest variation in the risk per serving, five were at restaurant step, two at market step, and two at farm step. For Ethiopia, the highest variation in the risk per serving due to *Campylobacter* spp. was due to six model inputs at home, two at market and one at farm. For *Salmonella* spp. in Ethiopia, the highest variation in the risk per serving was observed for five inputs at home, two at market and two at farm.

Paucity of data is always a major challenge in most QMRA studies (Nauta et al., 2005b). In this study, data for some model inputs, especially at farm and chicken slaughter steps, could not be found for Burkina Faso and Ethiopia (Table 1, and Appendix A, B and C). For example, the prevalence of *Salmonella* spp. in chicken feces at farm (Table 1) was

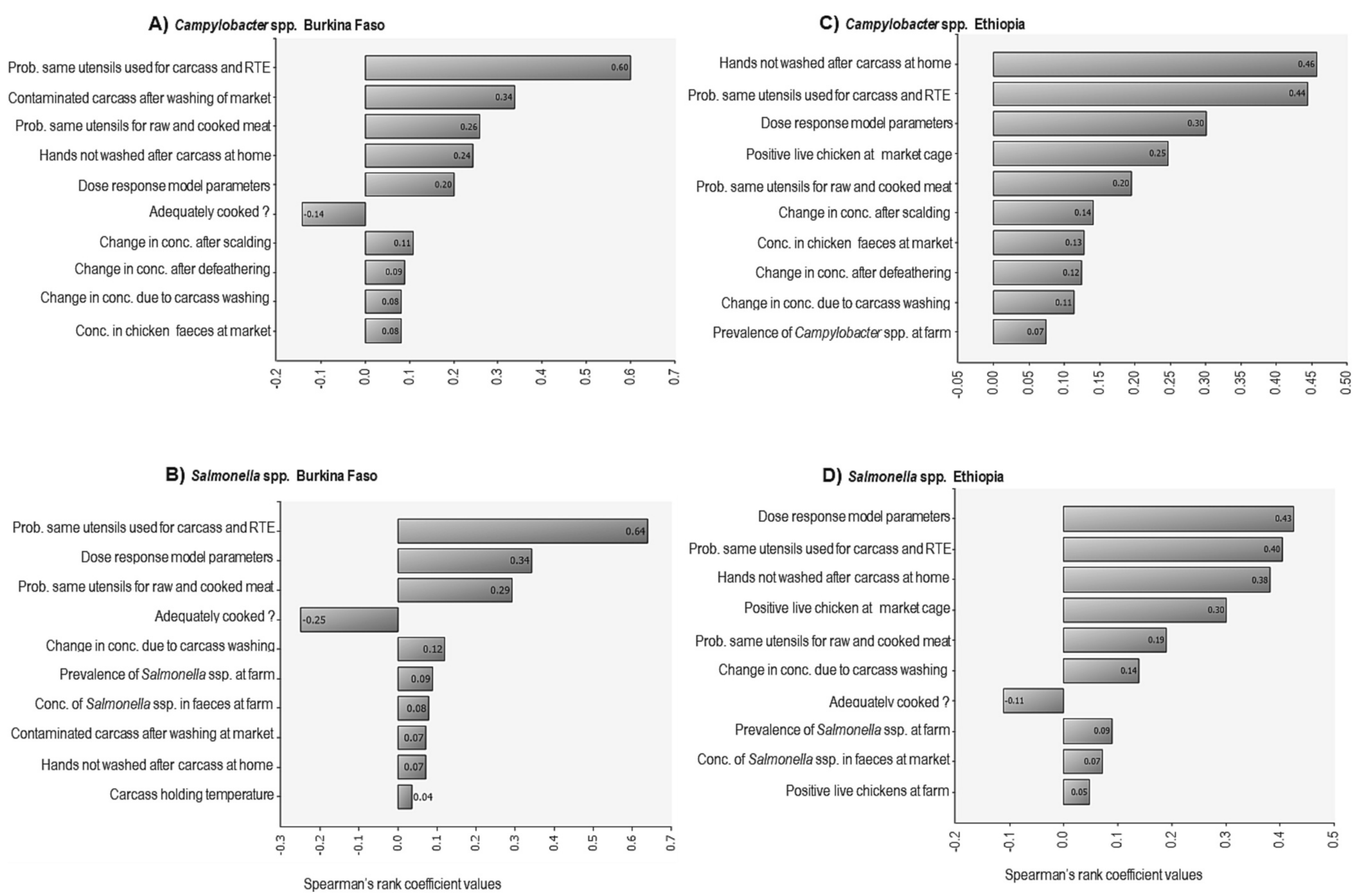

Fig. 3. Tornado plot displaying the first ten model input variables with the largest influence on the variability in estimated overall risk per serving due to consumption and preparation of chicken meat and ready-to-eat fresh salad potentially contaminated with *Campylobacter* spp. or *Salmonella* spp. Panel A and B are for *Campylobacter* ssp. and *Salmonella* ssp. in Burkina Faso while panel C and D are for Ethiopia, respectively. Spearman rank correlation coefficients were determined using Monte Carlo simulation (Latin Hypercube sampling) with 1,000,000 iterations of the four baseline models. RTE is ready-to-eat fresh salad, Conc. is pathogen concentration, Prob. is probability.

fitted from data obtained from various studies in different countries and this data can be hugely affected by sampling and laboratory methods. Annually over the whole country there is one percentage of chicken that is contaminated and prevalence should have a clear definition (prevalence of infected flocks, prevalence of infected birds, prevalence of contaminated samples). Furthermore, the data used in the slaughter steps were obtained from a systematic review of studies about industrial chicken processing in high income countries which may not reflect the situation in Burkina Faso and Ethiopia. In this study, we used a distribution to capture this data uncertainty and variability. Future studies on Burkina Faso or Ethiopia can pay special attention to these data gaps especially for those model inputs that manifest as key (Fig. 3). Further QMRA studies can also capture the different units of transfer rates rather than using them as proportion in the cross-contamination module and also the effect of native microflora as part of the pathogen ecology. In addition, future studies can explore the possible higher pathogen resistance or acquired immunity by personnel that participate in chicken slaughtering and cooking due to continuous occupational exposure, lower consumer resistance to subtypes on imported meat, buffering capacity of meals, severity of illness in different population groups, and the disease triangle (host, matrix, and environment).

3.4. Candidate *Salmonella* spp. and *Campylobacter* spp. intervention scenarios

Table 4 and 5 show the reduction in number of cases by each candidate intervention scenario for *Campylobacter* spp. and *Salmonella* spp., respectively. Candidate intervention scenarios were single actions, such as vaccination, or multiple actions in the same supply chain step, such as good hygiene practices and improved biosecurity, or combinations of separate intervention scenarios from different steps. Among the single action intervention scenarios in Burkina Faso, freezing at restaurants resulted in the highest *Campylobacter* spp. risk reduction (55 %) and 91 avoided DALYs per 100,000 people per year and using designated utensils at restaurants/homes in the second highest risk reduction (54 %) and 89 avoided DALYs per 100,000 people per year (Table 3). In Ethiopia, most effective *Campylobacter* spp. single action intervention scenarios were freezing (60 % risk reduction, 165 avoided DALYs per 100,000 people per year), designated utensils (37 %, 102 avoided DALYs) and hand washing by cooks at home (36 %, 101 avoided DALYs). For *Salmonella* spp. (Table 4), single action intervention scenarios with the greatest risk reduction were freezing (Burkina Faso 86 %, 1047 avoided DALYs; Ethiopia 87 %, 382 avoided DALYs) and refrigeration during carcass holding in kitchens (Burkina Faso 57 %, 692 avoided DALYs; Ethiopia 64 %, 279 avoided DALYs). *Salmonella* spp. is reported to survive freezing (Chaves et al., 2011) while for *Campylobacter* spp., reduction and inactivation has been reported (Rasschaert et al., 2020). The effect of freezing on *Salmonella* spp. and *Campylobacter* spp. in this study is therefore different. Due to freezing, a reduction in counts was applied for *Campylobacter* spp. in this scenario. For *Salmonella* spp. on the other hand it was assumed that inactivation due to freezing was not occurring (Chaves et al., 2011) but was preventing growth. Consequently, the growth module was removed from the *Salmonella* spp. model for this scenario and this action greatly reduced the eventual risk output compared to the other single action interventions. However, it should be mentioned that in practical situations freezing can damage muscles fibers, increase drip loss (Grashorn, 2010) and if the carcass is contaminated with pathogens, the resulting cross contamination can be larger. Intervention scenarios with one of the lowest risk reductions included improved cooking/roasting for both *Campylobacter* spp. and *Salmonella* spp. For improved cooking to appear to have a low-risk reduction is not based on the practical application but rather on the current settings in the baseline models. As shown in Table 2, for the intervention of improved cooking changes were made on the model input of the probability of undercooking. This model input only applies to route 4 and any intervention targeting only one route would at best

Table 6
Salmonella spp. risk reduction (%) after the intervention implementation targets of 25 %, 50 % and 75 % for the chicken meat supply chain Burkina Faso and Ethiopia.

Implementation target	Risk reduction⊕					
	Burkina Faso			Ethiopia		
	25 %	50 %	75 %	25 %	50 %	75 %
Candidate intervention scenarios						
Farm						
1. Improve biosecurity by changing to intensive farming system‡	33 %[a]	60 %[a]	82 %[b]	31 %[d]	63 %[d]	87 %[e]
2. Feed and water additives: Probiotics	- -	- -	- -	- -	- -	- -
3. Feed and water additives: Plant extracts	- -	- -	- -	- -	- -	- -
4. Feed and water additives: Organic acids	- -	- -	- -	- -	- -	- -
5. Vaccination	- -	- -	- -	- -	- -	- -
Transport of live birds						
6. Improved transport conditions of live birds	15 %[a]	29 %[b]	43%[b]	16 %[d]	31 %[e]	45%[e]
Market						
7. Avoid cross contamination between live birds at market	20 %[a]	39 %[a]	58 %[b]	47 %[d]	61%[d]	76%[d]
8. Good hygienic slaughter practices#‡	50 %[a]	65%[a]	77 %[b]	41%[d]	72 %[e]	84%[e]
9. Improved carcass washing at slaughter#	9 %[a]	24 %[a]	27 %[a]	13 %[d]	34 %[e]	52 %[f]
Transport of carcasses						
10. Improved carcass transport from market to restaurants	10 %[a]	19 %[b]	27 %[b]	**	**	**
Home/ Restaurants						
11. Improved hand washing after handling live and slaughtered chicken	4.2 %[a]	8%[b]	10 %[c]	20 %[d]	33 %[d]	42 %[d]
12. Refrigeration	- -	- -	- -	- -	- -	- -
13. Freezing	- -	- -	- -	- -	- -	- -
14. Designated utensils	30%[a]	50 %[b]	62 %[b]	23 %[d]	38%[e]	48%[f]
15. Improved cooking/ roasting	11%[a]	17 %[a]	21%[a]	0.5%[d]	1%[e]	1%[e]
16. Combined efforts at restaurant/home (Scenario 11+ 14 + 15)	44%[a]	75 %[b]	94 %[b]	66 %[d]	93 %[e]	98%[e]
Combined interventions at different steps of the supply chain						
17. Combined interventions at market and at home/ restaurants (Scenario 8 + 11+ 14 + 15)	63 %[a]	91 %[a]	98%[b]	**	**	**

- - Intervention evaluation did not use the % risk reduction approach of risk reduction target.
a, b, c, d, e, f Interventions with the same superscript letter across for a given country indicate that the difference in risk reduction for the implementation targets of 25%, 50% and 75% were not statistically significant.
For Ethiopia, these steps mainly occur at home.
⊕ Risk reduction was calculated by dividing the difference of the mean number of illnesses in the baseline and each hypothetical intervention scenario with the baseline mean number of illnesses multiplied by 100.
** Intervention scenario was not deemed feasible for the Ethiopia chicken meat supply chain.
‡ Multiple action interventions; these scenarios involve combining food safety actions in one supply chain step.

marginally decrease the risk estimates compared to inputs like pathogen prevalence that cut across different routes (Table 1), including those that are not targeted by the intervention. The risk reductions reported in this study for some interventions such as freezing and feed and water additives are close to those of the European Food Safety Authority (EFSA) studies (EFSA, 2011; EFSA, 2020).

Combining intervention scenarios (improved hand washing plus designated kitchen utensils plus improved cooking) resulted in 75 % risk reduction in Burkina Faso at restaurants and 93 to 94 % in Ethiopia at home. For Burkina Faso, adding good hygienic slaughter practices at the market to these combined intervention scenarios increased the microbial risk reduction to over 90 %. The efficacy of combined interventions was significantly higher compared to single action interventions because they target multiple risk factors that in most cases occur together for foodborne illnesses to happen. The evaluation of some interventions as presented in this study were based on 50 % implementation target (Table 2 and Table 6). Noticeably, the risk estimates changed when this 50 % implementation was substituted with 25 % and 75 % (Table 6, and Appendix E; Table E.1). Changing the implementation target from 50 % to 25 % lessened the risk estimates on average by 42 % to 44 % and when the target was changed from 50 % to 75 %, the risk estimates increased on average by 19 % to 28 % for both pathogens in Burkina Faso and Ethiopia.

Overall, our findings in Tables 4 and 5 suggest that combined intervention scenarios from different steps of the supply were more effective compared to intervention scenarios within a supply chain step. Noteworthy, the approach of implementing these intervention scenarios in Burkina Faso and Ethiopia may differ. For example, in Burkina Faso, the marketplace and the roadside restaurants are very critical to the chicken meat supply chain and if refrigerated and frozen storage of chicken meat is effective, it can be included in the regulations for the chicken vendors. However, for Ethiopia, the handling and storage of chicken meat takes place at home, so in this case consumer education can become vital. It has been argued that it is most efficacious to combine interventions, but there is a drawback of added cost and time of implementation that may render this strategy impractical (FAO & WHO, 2022). Cognizant of the issues surrounding the feasibility and affordability of implementing combined interventions, in this study we simulated combinations of intervention scenarios based on field conditions of the chicken meat supply chain in Burkina Faso reported by Dione et al. (2021) and in Ethiopia by Amenu et al. (2021). Lastly, it would be interesting to also assess the cost-effectiveness of these intervention scenarios (Van Wagenberg et al., 2016).

4. Conclusion

In this study, we developed a QMRA modelling framework that can be used for *Campylobacter* spp., *Salmonella* spp., or other pathogens to approach risk assessment tasks for chicken meat supply chains in African countries. This modelling framework can also be used to evaluate the impact of various candidate food safety interventions in the chicken meat supply chain that is typical of developing countries to support food safety management policy actions and also to guide research to fill the data gaps. Model results showed that effective food safety intervention for *Campylobacter* spp. and *Salmonella* spp. can be applied in all stages of the chicken meat supply chain. This study has demonstrated that interventions that target reduction in counts or inhibit growth (freezing) and cross-contamination from hands and food contact-surfaces are key. In Ethiopia, food safety interventions should focus at preparation at private homes and in Burkina Faso at the chicken market and roadside restaurants as shown by the outcome of intervention scenarios. Interventions that involve multiple food safety interventions in a step of the supply chain or combine interventions over different steps would result in more risk reduction and avoided DALYs than individual interventions. Overall, we envisage that by developing this QMRA framework, estimating the burden of *Campylobacter* spp., *Salmonella* spp. in chicken meat in Burkina Faso and Ethiopia, highlighting model input data gaps and testing various farm to fork interventions is a step in the right direction to guide risk-based food safety policy actions in Africa.

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CRediT authorship contribution statement

James Noah Ssemanda: Writing – original draft, Formal analysis, Conceptualization. **Heidy M.W. den Besten:** Writing – review & editing, Validation, Methodology. **Coen P.A. van Wagenberg:** Writing – review & editing, Validation, Methodology, Funding acquisition. **Marcel H. Zwietering:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Data availability

Data will be made available on request.

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Appendices. Supplementary data

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